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WG V: Phytoremediation and Bioenergy

Date:	05/02/2008
Prepared by:	Agata Drobniewska Department of Applied Ecology, University of Lodz European Regional Centre for Ecohydrology under the auspices of UNESCO, Polish Academy of sciences
Content:	The conceptual mathematical model for the sewage sludge management and biomass production in the Waste Water Treatment Plant

1 Summary

The general aim of the research on the WWTP is to show the alternative ways of the sewage treatment plant management in urban areas – closing the nutrient and pollutants cycle by conversion of these compounds into biomass and bioenergy by using ecohydrological measures. The studies in 2007 at the Protective Zone of the Waste Water Treatment Plant (WWTP) and the experimental willow plantation focused on: 1) continuation of the research conducted in the area over the last years and 2) development of the first version of the mathematical model based on literature review and the obtained results of the studies conducted so far. This report presents only the results related to the elaboration of the model. The aim of the model is to support decisions for the management of the WWTP system for an optimal use of the sewage sludge, heavy metals accumulation, biomass production, and generation of economical income. This model considers relationships between biotic and abiotic environment parameters influencing willow growth (module “Biomass production”), theaccumulation of heavy metals and application of possible sewage sludge doses (module of “Utilization sewage sludge”), and the economical benefits from the chosen management option (module “Economics”). The elaborated version is a conceptual model, and continuation of the studies allows for its calibration and validation. The model is addressed to the WWTP managers and other stake holders and authorities managing sewage treatment plants with consideration of both ecological and economical aspects. The users can set up such parameters as the ground water level, humidity of soils, soil pH, density of seedling, soil nutrients content (nitrogen, phosphorus, potassium), weeds biomass, heavy metals and organic matter content in soil and sewage sludge). The model calculates biomass yield, the amount of heavy metals removed, the sewage sludge applied and the income generated after a four-year cycle of production.

2 Introduction

In order to determine the biomass of energetic willow, the accumulation of metals by the plant, and efficiency of taking the metals in by willow, it was necessary to elaborate a mathematical model which would describe processes such as: growth of willow and crop of biomass, rate of photosynthesis, ground water level, humidity of soils, soils pH, density of seedling, content of nutrients elements (nitrogen – N, Phosphorus – P, potassium – K) in soil, weeds biomass, activity of pest, heavy metals and organic matter content in soil and sewage sludge amount of metals and organic matter in soil.

Mathematical model consists of three modules, whose names are:

1. Module of “Biomass production”
2. Module of “Utilization of sewage sludge”
3. Module of “Economics”

2.1 Module of “Biomass production”

The aim of this model is to estimate the potential biomass of willow after 4 years of plantation’s existence. The user of this model can manipulate: theamount of plants per ha, the pH, the biomass of weed [t d.w./ha] during the two initial years, the potential amount of animals on the plantation per ha, the groundwater level, and can take into consideration the prognosis of temperature and atmospheric precipitation (Figure. 1).

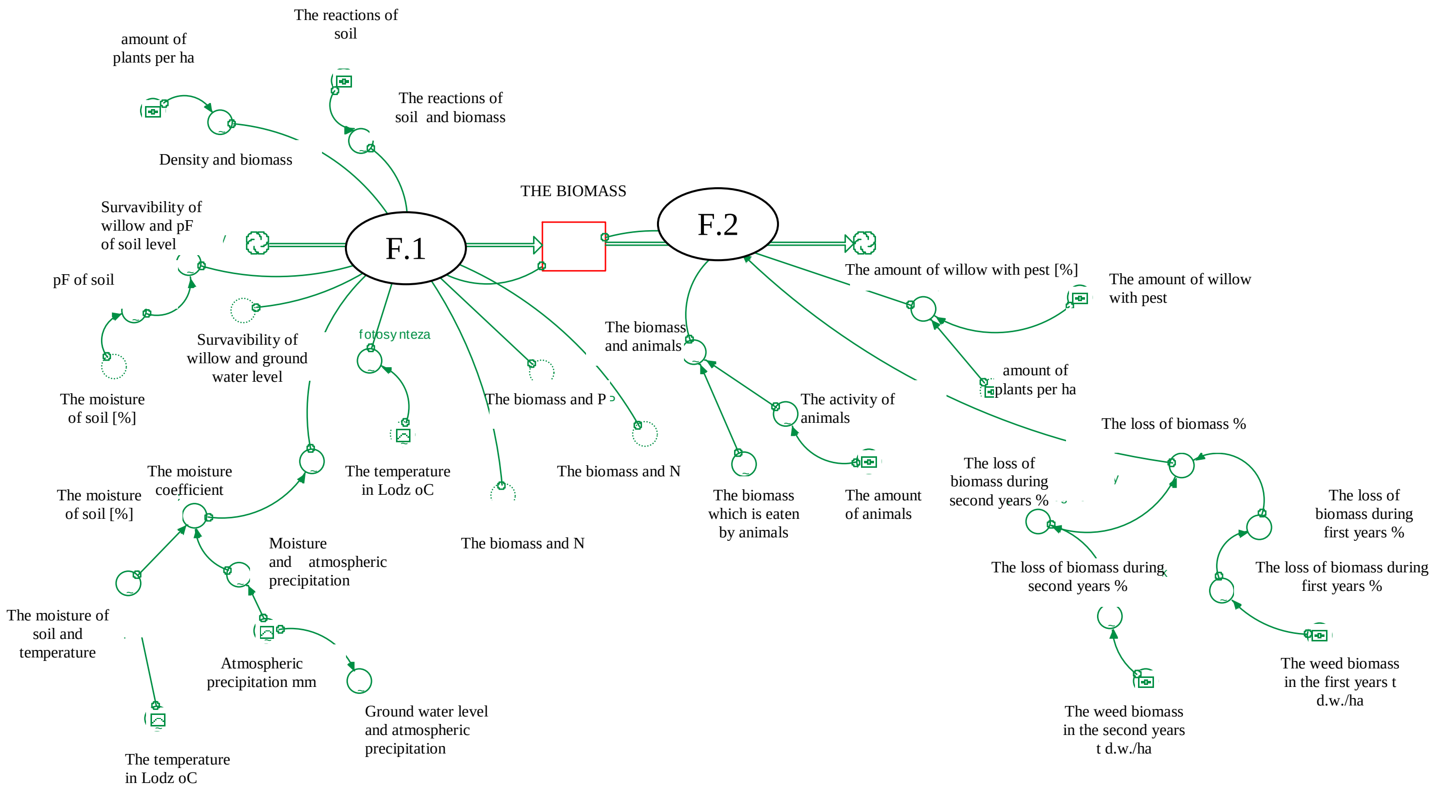

Figure. 1. The “Module of biomass productions”

The “Factor 1” (the positive impact) and “Factor 2” (the negative impact) create the “Biomass”, which is the function of time. The “initial biomass” is 0,5 t d.w. (Equation 1).

$$\mathbf{Biomass(t) = Biomass(t - dt) + (factor\_1 - factor\_2) * dt}$$

$$\mathbf{INIT\ Biomass = 0.5}$$

Equation 1. Differential equation „Biomass”

2.1.1 The increase during vegetation time and harvesting the willow's biomass

The vegetation period of willow in Poland begins during the spring and persists until the beginning of October (Figaj 1990). Numerous experiments with *Salix polaris* show that the optimal temperaturefor shoots to start growing is 15^{o}C (Chałupka 1990). The further increase of shoots can be observed during July and August (Dušek i Květ 2006). The reasons for it are: an optimal temperature, precipitation and humidity during this period of the year.

In case of the precipitation the most important are the two initial years. Too small precipitation during May – June is likely to result in thelowering of the willow's survivability due to insufficient development of the rootsystem (Dubas 2006).

In this model were applied the meteorological data obtained from the Institute of Meteorology and Water Management: an average month's value of temperature and an average amount of precipitation in the City of Lodz (Figure 2 a, b).

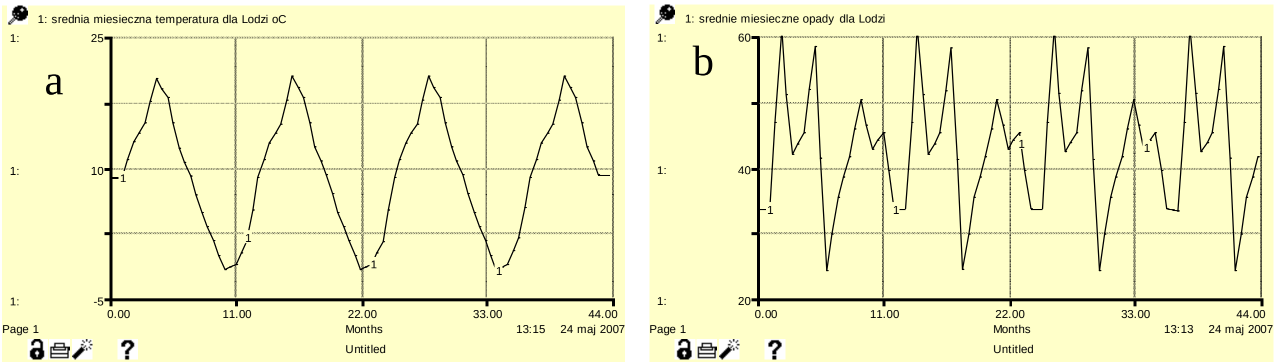

Figure. 2. The average monthly value of temperature (a) and the average of amount of precipitation (b) in the City of Lodz

The next important aspect is a harvesting time of the willow. According to Dubas et. al (2004), the largest biomass from willow it possible to be obtained after four years (after the first years there is a "sanitary" cut). This model of willow cultivation is the most effective as long as the use of biomass as energetic fuel is concerned.

Salix viminalis during the early part of growth time accumulate a large part of carbon in steams. In contrast, after three to five years the largest amount of carbon *Salix* is accumulated in roots. From this point of view the most advantageous is cutting down the willow after three years of growth.

2.1.2 The rate of photosynthesis

Among the factors influencing the biomass of willow are: the lenght of the day and a temperature. The most dangerous for the plant is a strong frost without snow. The short-lasting frost with a temperature below 10^{o}C is not harmful to the willow (Szczukowski and Budny, 2003; Dubas 2003; Dubas 2004; Kaszak 2006).

Thepresented model assumed that the optimal range of temperature for the photosynthesis is between 22 and 27^{o}C (Gorlach i Mazur 2002; Czerwiński 1977).

2.1.3 The groundwater level

The presented mathematical model establishes that the groundwater level is influenced by seasonal fluctuation. The values which were used in model describe the hydrological changes in the Protective Zone of the WWTP in the City of Lodz (Figure. 3).

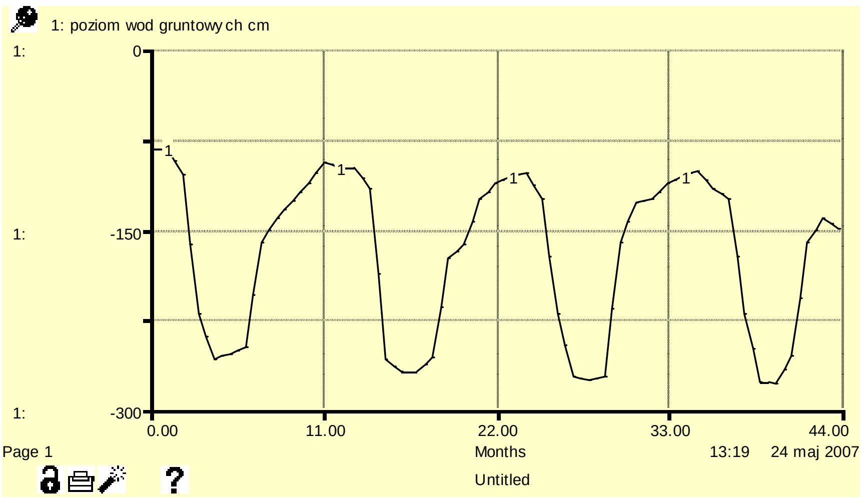

Figure. 3. The groundwater level.

The groundwater level depends on the precipitation, which was shown by Kozaczyk (2005). The plantation should be created in an area characterized by good irrigation. In case of the energetic willow it is important that the plant is not resistant to flooding. In the areas where flooding is observed, the survivability has been noted to last 2-3 weeks shorter (especially in the spring and summer (Kaszak 2006). In the areas with a permanent decrease of groundwater level a higher growth of the roots and the biomass can be observed (Figaj 1990).

Rogalewicz (2003) reported the highest biomass of *Salix viminalis* (RAPP, ORM, JORRUN, ULV and JORR) on the station with the lowest groundwater level (- 53 cm ÷ -98cm). According to the literature in this model it was assumed that the optimal level of groundwater is -100 ÷ -300 cm – on a sandy soil. In spite of it the groundwater level during the first year of plantation existence must remain above -50 ÷ -80 cm (Equation 2).

A p1 = IF(time<=7) then survivability_and_ground_water_level__in_1_year ELSE 1

B p1 = IF(time>7) then survivability_ and_ground_water_level_from_2_to_4_years ELSE 1

Equation 2. The groundwater influences on the survivability of willow during the first (A) and the second (B) years.

In the presented model it is established that the water level directly influences the survivability of the willow. This factor creates biomass during 4 years.

2.1.4 The soil moisture

The moisture of permanency wilting of plants (pF = 4,2) depends on the type of soils but not on the species of a plant. This factor is influenced by a temperature and the amount of the precipitation.

In this model, according to the literature (Gorlach and Mazur 2002; Korabiewski 2006; Czerwiński 1977; Kowalik 2001; Kowalik 1999; Bednarek at al.. 2004), it is assumed that the soil'smoisture level influences the soil's sucking force and the second on the survivability of plants.

2.1.5 The reaction of soil

The pH influences a plant's growth and development by modifying their nourishment. The optimum of the soil's reaction for the willow is between 5,5 and 6,5 and this value was assumed in the presented model. According to the literature the pH above 7,5 is not tolerated by the willow (Szczukowski 1998; Dubas and al. 2004; Kaszak 2006).

2.1.6 The willow density

According to the Twórkowski et al. (2005), the increase in the amount of plants per ha from 20 to 40 thousand plays a meaningful part in the increase of the biomass. The following increase of the plant it is not so important for the crop. The conceptual model presented assumes that the optimal number of willows is between 35 and 43 thousands/ha.

2.1.7 Content of nutrients elements (nitrogen, phosphorus, potassium) in soil

The nutrients content is the most important factor for the biomass growth (Gorlach and Mazur 2002). The requirements of the willow change in time and depend on the age. According to the Szczukowski and Budny (2003) the production of 10 tons of biomass per ha per year requires: 60 kg N, 8 kg P and 43 kg K. Numerous studies have shown that the required dose of fertilizers decreases as the willow's age increases. . During the first year the amount of nutrients is the lowest : N – from 20 to 30 kg/ha; P – from 10 to 20 kg/ha; K – from 20 to 40 kg/ha, during the next year the value is higher: N – 40 kg/ha; P – 60 kg/ha; K – 80 kg/ha; 3 years: N – 120 kg/ha; P – 90 kg/ha; K – 120 kg/ha; 4 years: N – 130 kg/ha; P – 100 kg/ha; K – 130 kg/ha). The time variation was demonstrated with the use of equations (equation 3).

Increase_of_biomass_and_N__during_4_years =
Increase_N_in_1_year* Increase_N__in_2_ year * Increase _N__in_3_ year * Increase _N_in_4_ year

Increase_P_in_1_year* Increase_P__in_2_ year * Increase _P__in_3_ year * Increase _P_in_4_ year

Increase_K_in_1_year* Increase_K__in_2_ year * Increase _K__in_3_ year * Increase _K_in_4_ year

Equation 3. The mathematical description of the willow demand during four years of willow growth.

The model takes into account doses of nutrients (N, P, K) present in the applied sewage sludge and fertilizers doses.

When taking into consideration the possibility of using the sewage sludge as a fertilizer it is important to note that the plant can take advantage of it through the vegetation time for even two-three years (Gorlach and Mazur 2002). The applied dose of sewage sludge was calculated basing on the regulations of the decree of the Ministry of the Environment (Dz.U.Nr 134, position 1140),as well as on the Nitrogen Directive (91/676/EWG).

In the presented mathematical model the amount of nutrients provided with a sewage sludge dose is presented in the module of “Utilization of sewage sludge”.
The amount of mineral fertilizers (Lacking of N, P, K) is obtained from the difference between nutrients requirements (N, P, K: 300, 300, 400 kg/ha respectively), and the amount provided with sewage sludge. The amount of nutrients to be supplemented with fertilizers is calculated basing on a difference between the plants nutrients requirements (N, P, K), and the amount provided with sewage sludge (Equation 4).

The lacking_N = N_need_for_willow-amount_N_in_applied_sewage_sludge doses_kg_na_ha_na_3_lata

The lacking_P = P_need_for_willow-amount_P_in_applied_sewage_sludge doses_kg_na_ha_na_3_lata

The lacking_K = K_need_for_willow-amount_K_in_applied_sewage_sludge doses_kg_na_ha_na_3_lata

Equation 4. The mathematical description of the quantity of nutrients elements provided on the plantation in mineral form.

The user can manipulate the quantity provided in mineral form [kg/ha], when the N, P, K deficit is known.

2.1.8 Weeding

In order to obtain a higher crop of biomass from the plantation the agrotechnical measure is needed (Stolarski 2004; Orwinska 2004; Dubas 2006, 2004; Kaszak 2006).
In this conceptual model it is assumed that if the plantation is weeding during the first two years, no problem with a loss of biomass during the next years is observed. This aspect was studied by Bergkvist and Ledin (1997). They noted the inhibition of the willow growth on the areas with a lot of weeds. It was the basis for the correlation between the willow’s biomass and weeding.

2.1.9 The pest activity

In the natural ecosystems the pests of insects and herbivorous mammals influence the willow’s biomass (Faliński 1990; Szmidt 1990; Tomczyk 2004; Dubas 2006; Dušek i Květ

2006). During the first year on the willow plantation there are a lot of pests, pathogens, bacteria, fungus and mammals (especially roe and deer). This is particularly observable in monocultures, that's why preservation of biodiversity is very important, as far as possible while maintaining economical benefits. It remains in agreement with the Habitat Directive (92/43/EEC), but it also influences the increase of the willow's biomass.

According to the literature, in this model "the activity of past" during the vegetation season was taken into consideration. It was dependent on the willow's density.This model also considered the potential activity of deer during the winter.

2.2 Module of "Utilization of sewage sludge"

In this module two parameters were included: the efficiency of soil and sediments remediation (the accumulation of metals in willow's biomass and a rate of the uptake of metals), and the calculation of the sewage sludge doses possible to apply on a willow plantation. The user can change the amount of metals in sewage sludge (mg/kg d.w. sewage sludge), the contents of N, P, K in sewage sludge, the amount of the organic matter (%), and in the end they are able to calculate the sewage sludge doses.

2.2.1 The efficiency of soil and sewage sludge remediation

The use of energetic willow as a remediation tool is an important ecological aspect. This problem was shown by Landberg and Greger (1996), Berndes et. al. (2004). The accumulation and rate of metals' uptake depends on: the amount of metals in an applied sewage sludge, the amount of organic matter in substratum, the substratum's reaction and the groundwater level (Figure. 4).

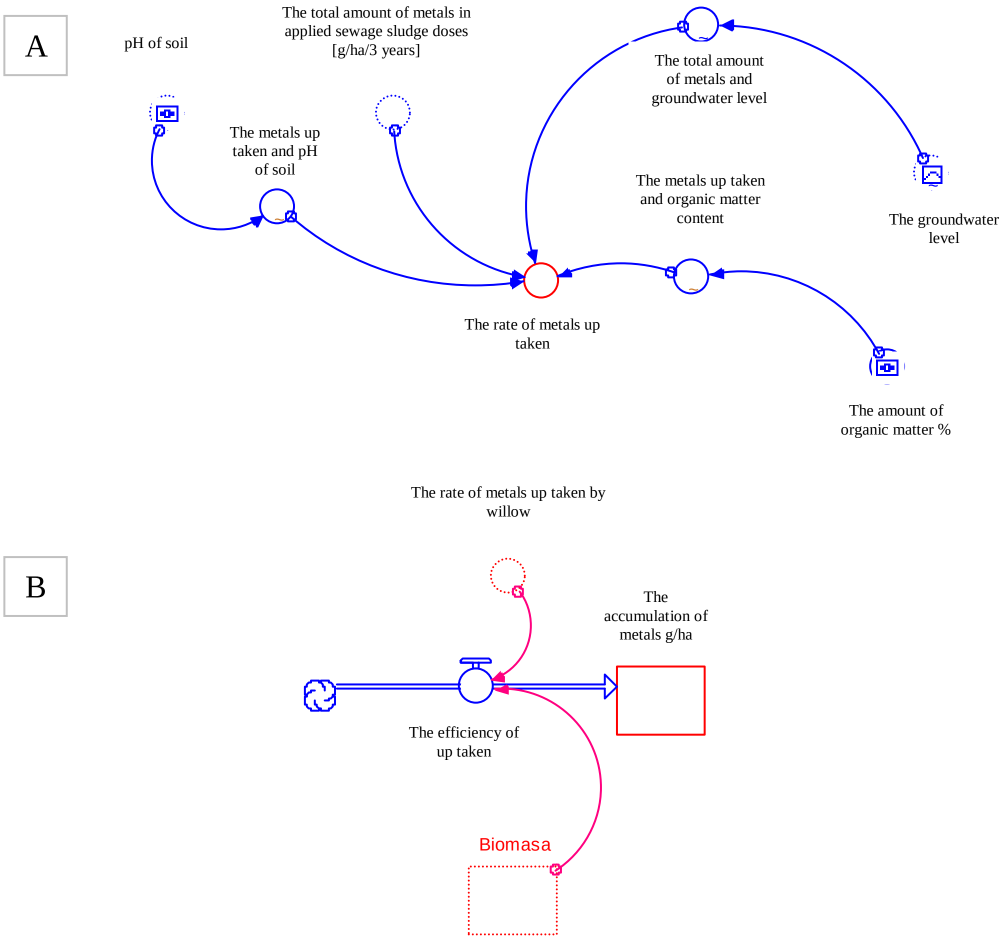

Figure. 4. Module of "Utilization of sewage sludge": A – the factors influencing the metals uptaken by willow; B – the factors influencing the willow's accumulation of metals .

2.2.1.1 The amount of metals in the substratum

The bioavailability of metals is not directly dependent on the metals' content and availability for plants (Gambuś and Gorlach 2000; Düring and Gäth 2002; Usman et al. 2006). However, Niebosiędzka (2000) proves it possible for the increase of the concentration of metals to result in the increase of the content of metals in plants. This assumption was taken in the presented model. The amount of metals applied on the plantations is calculated based on the doses of sewage sludge applied.

2.2.1.2 The content of organic matter in the substratum

The amount of organic matter influences the mobility and bioavailability of metals in the environment (Meregalli et al. 1999; Fernández et al. 2005, Karuppiah et al. 1997; Prokop et al. 2003; Gorlach and Mazur, 2002). According to the literature, when the amount of organic matter increases, the soil's sorption of metals increases as well, but the bioavailability decreases. The study of Rogalewicz (2003) shows that the concentration of metals in soils was 20 times higher in the samples with 15% of organic matter than in the samples with 1% of organic matter. The higher amount of organic matter in sewage sludge is important because of the decrease the of the toxic effect on plants and microorganisms (Prokop and Vangheluve 2003; Tate 1987). Benninger-Truax and Taylor (1993) show that the oxidation of the organic matter shows mobilization of metals in soil.

The presented modelassumes that with the increase of organic matter the amnount of metals in soil increases as well, but the bioavailability decreases.

2.2.1.3 The substratum reactions

According to literature, it is known that the pH is a factor which influences the rate of bioavailability of metals (Gorlach and Mazur, 2002; Düring and Gäth 2002; Kunito 1999; Bednarek and al. 2004; Siuta 1995, 1998). This impact depends on the plant's species and the type of metals. In the acid environment the bioavailability of metals increases and at the same time the accumulation of toxic substances in the organisms also increases (Kunito, 1999). In the presented model the total content of metals in the willow tissues increases when the pH decreases.

2.2.1.4 The ground water level

According to the experiments conducted by the Department of Applied Ecology, the groundwater level can influence the accumulation of metals in plant's tissues. The concentration of metals (for example lead – Pb) is higher in the areas with a higher ground water level, but simultaneously lower than in permanently flooding areas (Rogalewicz 2003; Wagner and al. 2007). This assumption was taken in the presented models.

2.2.2 Determination of the sewage sludge doses

The user of models can determine the sewage sludge doses thatcan be applied on the willow plantation, after including in the model physical and chemical parameters. These doses are in accordance with the Polish law regulations (Dz. U. Nr 134, poz. 1140. As the results the user obtains from the model the dose in tons which can be used on a ha area, total amount of metals (g/ha/3 years), and N, P i K (kg/ha/3 years) (Figure. 5).

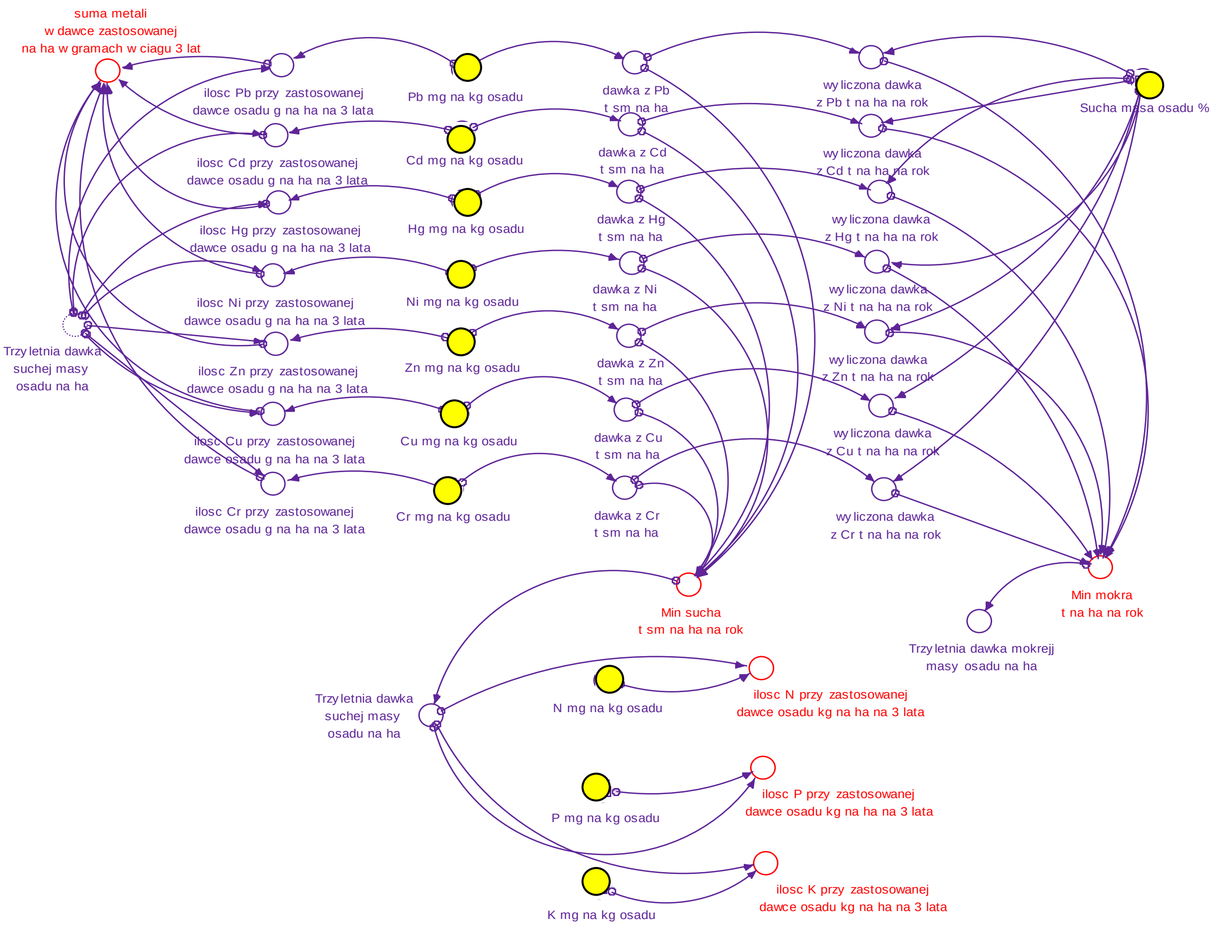

Figure. 5. The way for calculating the sewage sludge doses.

2.3 Module of "Economics"

The user can assume: the size of plantation (ha), the price biomass and caloric/energetic value.

Market research analyses show that willow fuel caloricity is twice lower than this of the hard coal. From 1 ha we can obtain 15 – 20 tons d.w. The caloric value of 1 ton d.w. is 10,4 GJ/t (Szczukowski 1998). Actually, the price of purchase is about 80 zł/t. The cost of 1 GJ is about 8 zł (Figure. 6).

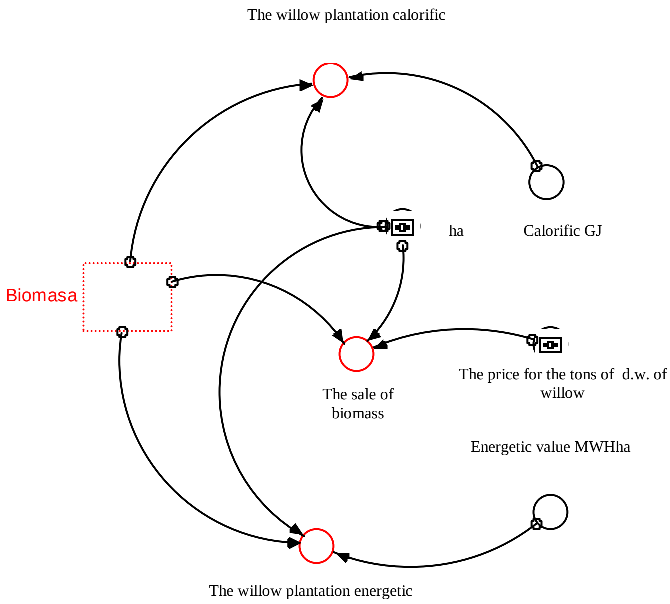

Figure. 6. Module of "Economics"

3 Conclusions and next steps

The presented mathematical model is a conceptual model for the sewage sludge management and biomass production in the Waste Water Treatment Plant. In the next years the model will be verified and calibrated on the basis of the experimental data. The effect of ground water effect and soil moisture on biomass production and heavy metals accumulation by the willow will be tested. In order to accomplish this goal, a network of piesometers will be installed, as well as the equipment for watering the plantation and applying sewage sludge, together with an on-line computer system for monitoring the environmental parameters. The study conducted in the previous years will be continued, including: analyses of content of organic matter in soil samples, soil's pH, soil's metabolism (system OxiTop ©-Control WTW), estimation of toxicity of soil samples (Phytotoxkit Tigret, Microtox), estimation of soil's moisture, the content of metals in soli (the availability form) and measuring the rate of growth of the willow and accumulation of metals. Other activities will include: quantification of energetic willow and energetic grass growth, and biomass production after treatment with vermicompost and sewage sludge.

4 Literature

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