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INTEGRATED WATER RESOURCE MANAGEMENT MODEL IN INDUSTRY

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Introduction

Relevance of the research

Water resources management has become an important operational and environmental issue. The demand for water resources is daily increasing in the world. In the past water was a cheap and abundant resource, the wastewater could be discharged in surface water or to the sewer system without excessive costs and restrictions. However, the rising costs of dependable water supplies and wastewater disposal have increased the economic incentive for implementing technologies that are more environment-friendly, and can ensure efficient use of natural resources. The key European Directive 61/96 *"Integrated Pollution Prevention and Control"* (IPPC) is going to be implemented in all European Union countries. The implementation of the Directive will be determinant in sustaining and encouraging water reuse and recycling application. The purpose of the Directive is to achieve integrated prevention and control of pollution arising from a large number of activities listed in its Annex I, leading to a high level of protection of the environment as a whole. The Best Available Techniques (BAT) will be defined for several industrial processes with a view to eliminate or reduce emissions. As far as the process industries are concerned, some of the BAT are likely to implement *closed-loop* options for industrial water usage. Implementation of IPPC is going to be determinant to the sustainable and encouraging water reuse and also to recycling application in Lithuania. The appropriate wastewater treatment and recycling is the way to break the negative impact of human activities on the environment. With the regulation becoming more stringent, the increase in water consumption efficiency is a relevant today's problem not only in Lithuania but also in EU and other countries of the world.

Lithuania, as all the other countries of the previous Soviet block, inherited economy with very ineffective use of water and other different natural resources. To produce one unit of GDP Lithuanian economy consumes several times more natural resources than EU15 average. Not so long ago Lithuanian enterprises were achieving the necessary minimal pollution level by diluting wastewater at the end of the pipe. It was the only way to avoid huge fines imposed by environmental specialists. Today this practice is no longer rational, and also makes huge economical damage to the interests of the company. On the other hand, the wastewater treatment is costly, and Lithuanian enterprises are facing a great need of starting the recycling of wastewater and introducing various types of systems for the water reuse.

In Lithuanian strategy for sustainable development the attention is paid to elevating the ecological effectiveness of production and services. Actually, our strategies lack clarity and models for saving water resources in the country, and this problem raises new challenges for Lithuanian science.

Object of investigation – technological flows of fresh water resources and wastewater in the enterprises of process industry.

The aim of the research – to investigate and evaluate the criteria for water use and reuse, and to develop a model for effective management of water resources in industry.

The following main tasks were raised for this work:

1. To analyze the preventive methods of saving water resources, minimizing wastewater amount and applying the advanced wastewater regeneration technologies.
2. To investigate the possibilities of effective water resources consumption in Lithuanian industry by performing comparative analysis of water consumption in different branches of process industry and evaluating the potential of water resources saving.
3. To develop the model for integrated water resources management (IWRM) *("Integruoto vandens išteklių valdymo modelis", IVIV, Lith.)* in a company.
4. To identify the criteria for efficient water consumption using IWRM model.
5. To investigate the possibilities of water reuse and water reclamation for a closed loop in different industrial companies.
6. To carry out an experiment of wastewater reclamation using selected technologies in an industrial company and to evaluate the possibilities of reclaimed water recycling and reuse for technological processes.

Scientific novelty and practical significance

The novelty of this work is *IWRM model,* which is designed for water resources management in the company and provides the possibilities for process integration and advanced wastewater reclamation technologies according to the mathematically formulated *efficient water consumption criteria based on an optimal solution approach*. The model also integrates the economical parameters such as water costs, water treatment cost, etc.

Up to the present time the research in the field of water resources consumption in Lithuanian companies was referred to only to the concept of cleaner production ("good housekeeping", process control and technological changes).

Approbation of the work

The results of this research work are published in 5 publications, 2 of them are in the accredited publications of the Lithuanian Scientific council. In addition, the papers were presented in 3 international conferences.

Some scientific research was performed in cooperation with the Center of Industrial Water Management at Danish Technical University as a part of the *EU 5th Framework* project *"INNOWASH - Minimization of water consumption in European textile dyeing and printing industry using innovative washing and water recycling technologies*".

Doctorate thesis comprises*:* introduction, 5 chapters, basic conclusions and references. The work consists of 124 pages, 48 pictures and 28 tables. 112 sources are presented in the references.

1. Water resources management and environmental protection

Wastewater reclamation and reuse are an effective tool for sustainable industrial development programs. The appropriate wastewater treatment and recycling is also the way to eliminate the negative impact of human activities on the environment. The chapter "International Experience and Results" gives the review with the aim to increase water consumption efficiency using preventive technologies. The increase in water resources consumption efficiency is understood as the decrease in water amount, which is used on the released production (GDP) without the simultaneous decrease in the quantity of released production but with the warrant of the environmental requirements. The basic legal documents and strategies of international importance which regulate the water efficiency consumption and the decrease in an environmental impact are reviewed.

In this chapter the methodologies of systematic evaluation and minimization of water resources consumption are discussed. An attempt to evaluate the needs, possibilities and possible effectiveness of such worldwide approach as "water pinch analysis" is also made. Water pinch analysis is a technology providing a systematic approach for minimizing the use of fresh water and the discharge of effluent water without losing sight of the costs. It is a strategic tool for water management in industry. The fundamental theoretical formulations for the application of the pinch concept to wastewater problems were amongst others pioneered by *El-Halwagi and co-workers* (1992, 1995), *Smith and co-workers* (19994, 1996), *Wang and Smith* (1994a,b, 1995), *Kuo and Smith* (1997, 1998), *Alva-Argáez at al.* (1998a,b). The design methodologies and approaches cover a variety of techniques ranging from *the graphical based water pinch analyses* (Wang and Smith, 1994; Hallale 2000), *the source-sink graphical methodology* (El-Halwagi, 1997) to *mathematical optimization based approaches* (Keckler and Allen, 1999; Alva-Argaez et al. 2000). All these methodologies have a number of benefits and drawbacks but the major issue encountered is the expertise required for the practicing engineer to apply these techniques successfully (*Dunn and Wenzel, 2001*). The wastewater reuse potential for industries was determined and the types of industries that could benefit from wastewater reclamation and reuse were discussed. Various technologies for wastewater treatment and regeneration were presented. Nowadays *biological treatment* and *membrane technologies* are identified and recognized as the most suitable treatment for the industrial wastewater reclamation.

Several industrial branches having been analysed, the basic water consumption indicators in different Lithuanian industrial companies are compared with those in foreign countries practice. For example, water consumption in different companies of yarn industry (see Fig. No.1) is much higher compared to water consumption using Best Available Techniques (BAT).

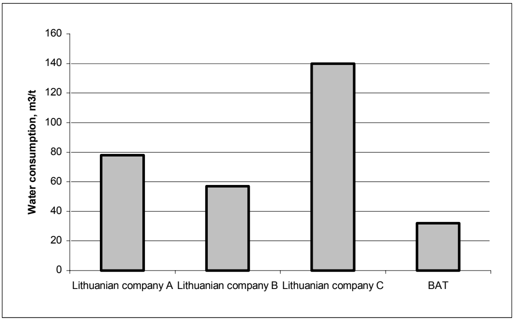

Figure 1. Water consumption in yarn producing companies

The costs increase for water consumption and wastewater treatment (see Fig. No.2), compelled Lithuanian companies to look for new ways of economic effectiveness. Compared to the companies and enterprises of developed European countries, the tendencies for water consumption and the problems of the effective use of wastewater are common for most of the industries in the country (food, chemistry, electronics, etc.).

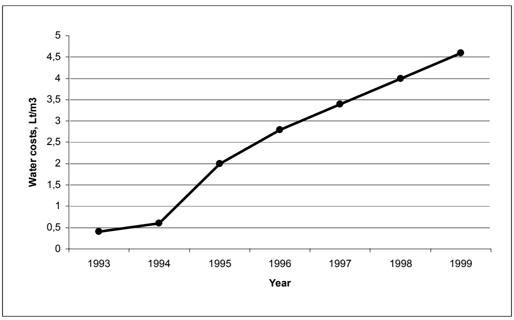

Figure 2. Costs for water supply and wastewater sewerage in the period 1993-1999.

After analysing the world practice and various means of pollution prevention, cleaner production and environmental management projects implemented in Lithuanian companies, the following conclusions used for further investigations have been made:

1) There is a huge potential for water reuse, water recycling and closed water cycles in most of the companies of different industrial branches.
2) Textile, pulp and paper, chemical, food and metal processing, power generation industries have the greatest possibilities of minimizing water consumption and wastewater.
3) Compared to water usage known in foreign practice, many Lithuanian companies exceed water consumption several times, in some cases even more than ten times.

The problem of ineffective water treatment in industrial companies served as a basis for choosing the subject matter for this scientific research work.

2. Methodology

The research work on saving water resources in various industrial companies has been done consequently in several stages:

1) Theoretical analysis of the research performed in situ. At the beginning of the research, the effectiveness of water consumption in different Lithuanian companies has been analyzed and compared to good practice examples from the EU developed countries and worldwide.
2) The water saving potential in process industry companies has been determined.
3) The detailed analysis of "Water Pinch" method and the experiment of process integration in a company have been carried out.
4) The experiments of membrane filtration have been made and the possibilities of reclaimed water reuse have been evaluated.
5) The IWRM model methodology for estimating economical benefits has been applied in a company.

2.1. Process integration methodologies for water network optimization

Process integration represents an important branch of process engineering. It refers to the system-oriented, thermodynamics-based, integrated approaches to the analysis, synthesis and retrofit of a process plant. The main goals of process integration *(PI)* are to integrate the use of materials and to minimize the generation of wastes. A recent development in pinch technology that deals with pollution prevention, resource recovery, and waste reduction is mass-exchange integration. In identifying water reuse and recycling opportunities a systematic technology by means of a graphical tool for analysing water networks called the water pinch diagram was introduced by *Wang and Smith (1994)*. The water pinch diagram is used to identify key design targets such as the minimum amount of fresh water required by the studied system, the amount of water recycling and achievable reuse, and the water quality concentration bottleneck.

In order to maximize the possibility of water reuse from processes, the highest possible inlet concentration should be specified. The changing of the inlet concentration of water used in a process results in a change of outlet concentration. The maximum available effluent concentration should be determined and compared to the resulting one when increasing the influent concentration.

The minimum flowrate when setting for the maximum inlet and outlet concentrations is called *the limiting water profile*. The minimum flowrate f can be mathematically expressed in the following way *(Wang and Smith, 1994)*:

$$f_i^{\lim}(m^3/h) = \frac{\Delta m_{i,tot}(kg/h)}{[C_{i,out}^{\lim} - C_{i,in}^{\lim}](mg/l)} x10^3 \qquad (1)$$

$C_{i,in}^{\lim}$, $C_{i,out}^{\lim}$ - inlet an outlet limiting concentrations;

$\Delta m_{i,tot}$ - total mass load of contaminant to be transferred;

In the case of full regeneration, mass load Δm_{regen} of contaminant regeneration transferred to freshwater stream f_{min} prior to regeneration is

$$\Delta m_{regen} = f_{min} C_{pinch} \quad (2)$$

The mass load of contaminant transferred to the regenerated water stream between regeneration-outlet concentration C_0 and freshwater pinch C_{pinch} is

$$\Delta m_{pinch} - \Delta m_{regen} = f_{min}(C_{pinch} - C_0) \quad (3)$$

Thus, the total mass load of contaminant transferred prior to the freshwater pinch is the sum of Eqs. (2) and (3)

$$\Delta m_{pinch} = f_{min} C_{pinch} + f_{min}(C_{pinch} - C_0) \quad (4)$$

Rearranging Eq. (4), we find the minimum freshwater flowrate for simple full-regeneration problems in terms of freshwater pinch C_{pinch} and regeneration-outlet concentration C_0.

$$f_{min} = \frac{\Delta m_{pinch}}{[2C_{pinch} - C_0]} \quad (5)$$

f_{min} – minimum freshwater flowrate (m^3/h).

2.2. Criteria of efficient water resources consumption

The main criterion for efficient water use W_w is based on the necessity of minimizing water consumption in companies.

$$W_w \rightarrow \min \quad (6)$$

At the same time, it is important to keep a high productivity rate and meet the environmental requirements of EU standards.

$$N = const; \quad (7)$$

$$Q \geq Q_{min}; \quad (8)$$

W_w – quantity of consumed water
N – production quantity which is required to be produced
Q, Q_{min} – production quality indicator and its minimal value, respectively.

Two theoretical criteria were settled for further estimation:

1) the decrease in water consumption for producing a production unit;
2) minimization of water costs.

The decrease in water consumption for producing a production unit

In the process industry *expenditure of water resources (E_w)* for a unit of product is the main criterion (indicator) of efficient water consumption

$$E_w = \frac{W_w}{N} \tag{9}$$

This criterion has to be followed by every enterprise, which uses water in its technological processes and seeks to minimize water consumption

$$E_w \rightarrow \min, \tag{10}$$

Minimizing water costs

This criterion can be followed in every enterprise calculations of water resources and wastewater treatment expenditures, regardless the type of industry or technological process used in the company

$$K = \sum tW_w + rW_{ww} + W_{other} \tag{11}$$

K – costs of water consumption in the company
W_w – the amount of water consumed
W_{ww} – amount of discharged wastewater
W_{other} – other costs related with water resources
t – tariff of water resources
r – tariff of discharged wastewater

In this case the objective to be achieved is the decrease in costs of water resources consumption, under conditions (7) and (8)

$$K \rightarrow \min, \tag{12}$$

2.3. Wastewater regeneration by membrane technologies

The membrane filtration experiments on rinsing water after reactive dyeing of cotton were made at a textile company in Germany. Experiments were performed with *a DDS 20 pilot scale membrane filtration equipment (Fig. 3)*. This system operates over the pressure range of 1-70 bars and a maximum of 0.7 m^2 of total membrane area. The process performance was controlled by measuring the permeate flow and the pressure at the inlet and outlet of the module during experiments.

Figure 3. Pilot scale membrane filtration equipment DDS 20

The permeate samples were examined after the membrane tests were collected for water quality analyses and washing test. Colour was measured by a VIS/UV spectrophotometer (PERKIN ELMER Lambda 7). COD was estimated by WTW Photometer MPM 3000, pH was measured with an ion analyzer Merck QpH 70, and WTW LF318/SET instrument was used to measure conductivity. Washing out tests were done on AHIBA Texomat equipment. For wet rubbing fastness evaluation ATLAS-Textile Testing Products, CM-5, AATCC Crockmeter was used.

3. Integrated water resources management (IWRM) model

In *chapter 3* the model for Integrated Water Resources Management *(IWRM)* in process industry is presented (Fig. 4).

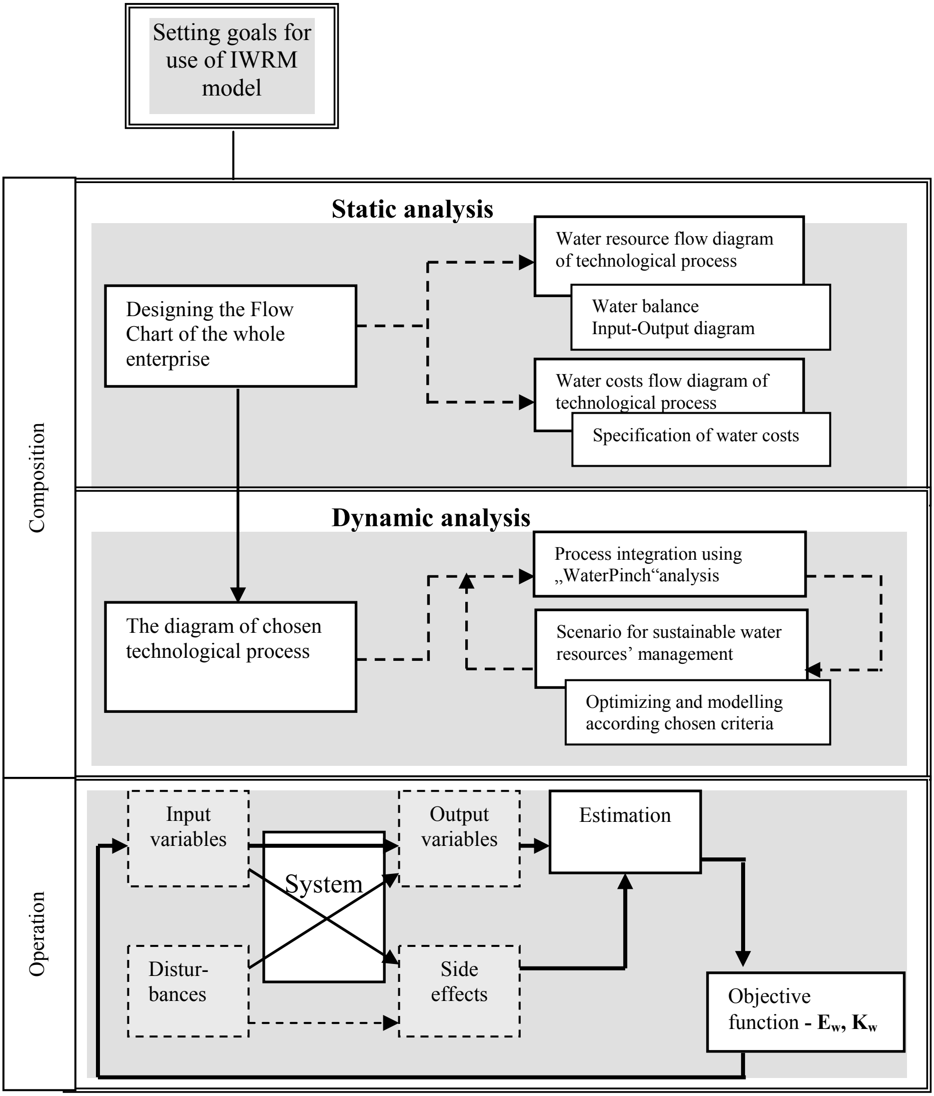

Figure 4. The structure of a model for Integrated Water Resources Management (IWRM) in industry.

The model is a useful tool for investigating complex water used in production systems. The model enables researchers to analyse the process water system in a static domain, given by a certain time frame, and in a dynamic domain, where time dependant changes can be monitored. The step-by-step procedure and the consistent relationships between the input-output diagram types allow the straightforward set-up execution of a water saving project.

The Static diagram types reveal the structure of the system i.e. flows and processes. A system optimisation is possible based on both water and costs which are calculated and balanced by water resources and wastewater in order to point out possible savings. The diagrams are hierarchally structured in several levels of details allowing an in-depth analysis of complex systems with numerous sub-systems. The Dynamic analysis involves a water analyses technology called "WaterPinch" for analyzing water networks, which provides a systematic approach for minimizing the use of fresh water and the discharging of effluent water without losing sight of the costs. The detailed water network analysis enables researchers to find out the best water recycling solutions using wastewater regeneration technologies. Membrane technology was chosen as an example of the regeneration experiments of process water for reuse. Membrane technology is now consistently proving to be a commercially viable alternative to discharge off effluents directly to drain. It is not a panacea for effluent treatment problems and it is still important to seek for an expert advice, and carry out extensive trials, in order to ensure that the technology will be compatible with the application.

Application of IWRM model. There are two main areas for applying IWRM model: 1) technological process in appropriate equipment, which uses water resources (*a simple object*) and 2) technological chain consisting of several technological processes or equipment consuming water (*a complex object*).

Usually, technological processes are affected by various factors (variables), such as:

a) *Input variables* $x_1, x_2,...x_n$ - which are described by quantitative and qualitative parameters of water consumption. This can be water resources from different sources of water supply – supply agent, own bores, and also the information on the water resources: amount, concentration of separate components, temperature, etc.

b) *Output variables* $y_1, y_2,...y_n$ – these are waste water flows from different technological processes and pollution concentration as well as temperature. These values determine the process mode and describe the state of a technological process.

c) *Disturbances* $t_1, t_2,...t_n$ – effects regarding the changes of water quality, resources limits, changes of legislative requirements.

d) *Control parameters* $u_1, u_2,...u_n$ – changing regimes of technological processes and the compensation of existing interferences.

Assessment of technological object relations between these parameters is stipulated. This process can be viewed as demonstrated in Fig.5.

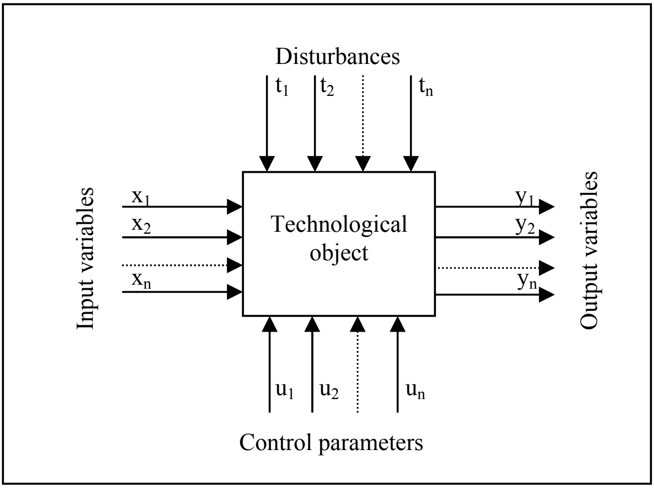

Figure 5. Structural scheme of technological object

Principle of IWRM model operation

The IWRM model operation is based on *the optimal solution approach*. The optimum control is a feedback strategy using a combination of the costs of control and system costs as an objective function, and using the system model as a linear constraint. An objective function is understood as water resources usage rates per production unit E_w or minimization of wastewater treatment costs *K*.

The IWRM model is employed for optimisation of the objective function with regard to quality and environmental requirements (Fig. 6). This model makes it possible to keep the system in balance foreseeing the preventive measures for waste minimisation. When applying the model in a selected enterprise, all possible ways of water should be systematically assessed, i.e.:

a. Implementation of the direct water recycle;

b. Water collection and reuse in technological processes;

c. Application of regenerative technologies for wastewater treatment;

d. Development of closed water cycles for separate production lines or for different technological processes;

The IWRM model *(see a detailed scheme in section 3)* consists of two separate parts:

1) *Static analysis* – diagrams for separate production processes, water flows and costs balances;

2) *Dynamic analysis* for development of sustainable water use scenarios in an enterprise – for evaluation and assessment of pollution quantities in different technological processes; for systematic measurement of water recycles, and creation of water reuse and closed water cycles; for modelling of water flows integration and optimization with regard to the production programme (depending on time, e.g. week or month).

Special software for modelling the scenarios for sustainable resource management and the criteria for effectiveness of water resource savings proposed for enterprises are described in detail in section 2.2.

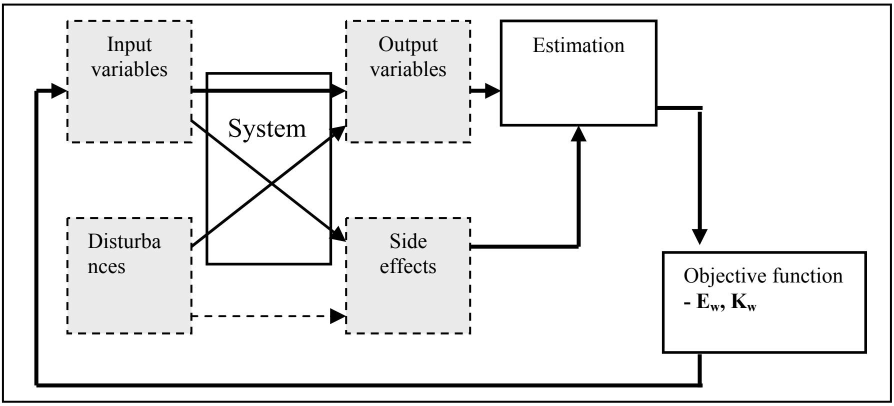

Fig. 6. Principal operational scheme of IWRM model.

The model allows systematic evaluation of the possible scenarios for minimization of water resource expenditures and for their effectiveness. If the calculated values are not in line with the nominated ones, then it is possible to revise the input and output variables and to re- evaluate the incidental impacts in order to correct the production technology management.

The presented IWRM model complies with all basic stages of the enterprise management – planning, assessment, performance analysis, implementation, monitoring and improvement. One of the most important elements of this model is a continuous improvement. The single analysis of the possibility to save water resources and minimize wastewater can also be economically effective, but it does not provide any guarantee that of the success of such measures. Only continuous monitoring of primary water source balance and continuous updating of the data from water flows, water and wastewater costs fixation, and the analysis of financial accounting indicators are the only conditions guaranteeing the minimization of costs concerning the enterprise water usage.

4. Application of the IWRM model

Chapter 4 presents the application of theory to practice, the use of the *IWRM* model for saving water resources and minimizing wastewater in different industrial companies. The majority of experiments on saving water resources by using the *IWRM* model have been performed in different industrial companies. They have been mostly made in textile companies. Why have the textile companies been chosen for the experimental work? The textile industry wastewater is a significant source of pollution containing high concentrations of inorganic and organic chemicals and is strongly coloured by the residual dyestuffs. Thus, generated effluents contain a wide range of contaminants, such as salts, dyes, surfactants, oil and grease, oxidizing and reducing agents. In environmental terms these contaminants are suspended solids, COD, BOD, as well as high pH and very strong colour. The goods are usually washed too long and too intensively and in order to achieve the best rubbing and wash fastness wastewater is drained directly into the waste water treatment plant without any recycling or cleaning.

To apply the IWRM model the following steps have been used:

- identification of the machine groups with the largest annual water consumption;
- investigation of machine groups with regard to possible direct water reuse, theoretically and in practically;
- evaluation of direct water reuse solutions;
- estimation of the value of direct water reuse initiatives;
- selection of relevant technology able to work in the process water from rinsing after cotton dyeing;
- estimation of the reduction in polluting substances in the reclaimed process water after membrane filtration;
- determination of the applicability of this permeate for reuse as rinsing water in the dyehouse;
- evaluation of economic efficiency of water reclamation by membrane filtration and reuse in processes.

In this chapter the data on water resources are used for more detailed analyses. First, the water consumption analysis is conducted. Then, the theoretical water reuse target has been estimated. The water consumption analysis has confirmed that the washing and rinsing are two of the most common operations in the textile industry and optimisation of washing efficiency can conserve significant amounts of water. In overflow rinsing, clean water is fed into the machine and drained through an overflow weir usually set near the normal running level. This technique is useful for removing the surface scum resulting from poor quality water or chemicals or from inefficient pre-treatment. In terms of water consumption, it is inefficient especially with a high liquor ratio. Furthermore, the analysis has clearly shown that the washing machines are also consuming a lot of water resources.

Chapter 4 says that determination of a well founded estimate of the possible maximum reuse of water at textile, leather companies assuming that the available sources of water could be combined with the available sinks in the absolute optimal way while ignoring any practical obstacles is one of the goals of this work.

Wastewater regeneration by membrane technologies

Biological treatment, chemical precipitation, membrane technology, activated carbon adsorption and evaporation are the common wastewater treatment techniques of textile industry effluents. Low salinity rinse water can be treated with all four techniques. However, membrane filtration is technically advantageous compared to other techniques. Process water membrane filtration in the textile industry has been reported as a favourable answer on water reuse requests. The hot rinsing water reclaimed by membrane filtration has been tested on a number of recipes and successfully used for rinsing. The hot water reuse speeds up the rinsing process compared to the traditional recipes, thus saving 50% of the time consumption for rinsing, and thereby increasing the equipment production capacity. However, several comprehensive case studies should be accomplished for different textiles, recipes and machines used in different dyehouses.

Membrane filtration experiments have been done in cooperation with scientists from Danish technical university and a textile company. Six from the 14 membranes used for the task have been received at textile company and have been selected by laboratory experiments at IPU for the further pilot tests of this project. Nanofiltration membranes have been supplied by Osmonics (Desal DK and Desal DL) and by DSS (NFT 50). Reverse osmosis membranes have been supplied by Film Tec (BW30), by DSS (HR98), by Osmonics (Desal SG).

Characteristics of permeate and washing results

Nanofiltration and reverse osmosis membranes at a dyehouse have been evaluated for their ability to separate colour, COD and conductivity of the process water coming from the washing machine. As an example, the results of the permeate quality at different concentration degrees (CD) are presented (Fig. 7). The permeate from the NF membranes is not colourless at CD5, while permeate from the RO membranes are always colourless or nearly colourless. Almost complete colour removal has been achieved with the reverse osmosis membrane filtration.

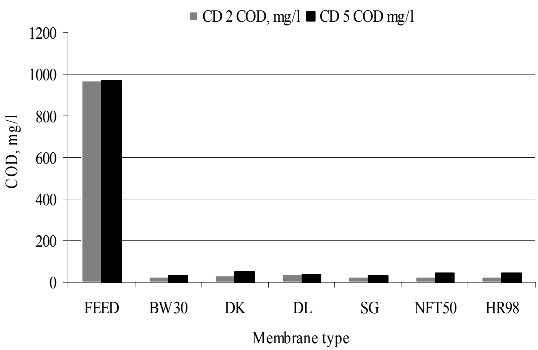

Fig.7. COD retention

The feed COD value was between 920 mg/l - 966 mg/l. COD retention of the NF membranes was around 95% for the RO membranes, the COD retention was around 97%. In some examples the COD was lower than 10 mg/l. The rinsing *(washing out)* tests were performed on an AHIBA Texomat apparatus at the laboratory at ITC in Denkendorf. Tests were performed by rinsing of cotton textile dyed at the dyehouse. The rinsing effect of permeates from the different membranes (Fig.8.) did not differ from that of fresh water.

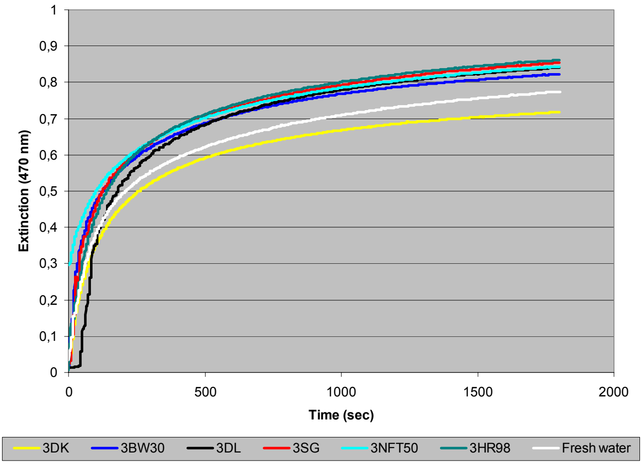

Fig.8. Rinsing test

In the future the main challenge for water professionals is to provide new engineering solutions such as membrane technologies for better management and closing the water cycle in both small and large industrial companies. The appropriate wastewater treatment and recycling are the way to break negative impact of human activities on the environment.

When carrying out the case studies, it has been found out that a IWRM model is applicable to various types of water using production systems, especially to those consuming large water amounts. For example, using the IWRM model in testified textile companies 52-62% fresh water savings have been achieved, and a correctly applied membrane filtration makes it possible to create a closed water loop for a textile rinsing process. Integration of “WaterPinch” and wastewater regeneration technologies ensure process optimization, they can provide financial savings, conserve natural resources and help to meet the present and future environmental legislation requirements.

5. Conclusions

The results of the research work performed allow to draw the following conclusions:

1. The comparative analysis of water resources in industry has shown that the main criteria for effective water use are an *input of water resources used for producing a unit of the production (m^3/t, pcs., m)*. Comparing these criteria among industrial enterprises of developed countries following BAT recommendations, Lithuanian enterprises use *3-5 (in some cases 10)* times more water for a production unit, especially *in textile, pulp and paper, metal processing, chemistry and food industries.*

2. The model of *Integrated Water Resource Management* (IWRM) helps to assess and evaluate systematically water resources and wastes in the enterprise. Applying this model to the enterprise there is a possibility to create various scenarios for optimal management of water resources: *for the use in a total or single technological production process.*

3. The analysis of the IWRM model effectiveness has indicated that in a case of a big enterprise of the textile industry, application of the IWRM model allows to save *52%* of water resources for 1t of the production and in a case of a small textile enterprise – savings of *62%* of water resources are calculated.

4. The experimental results of waste water regeneration using the membrane filtration in a chosen textile enterprise allow to draw the conclusion that the regenerated water can be used not only for water recycles or in closed cycles, but also for other various types of technological processes.
   4.1. Using membranes *NF* and *RO* for wastewater regeneration in textile, the effectiveness of removing the intense colour from wastewater is *95-100%.*
   4.2. The effectiveness of contaminant removal from wastewater according COD and conductivity is *95%* when using NF membrane, and *97%* when using RO membranes.
   4.3. After introducing the closed wastewater cycle for washing in a rinsing machine the savings of an enterprise are *86%* per year.

5. After implementing the IWRM management model in a chosen textile enterprise which uses 800 000 m^3 of water, the savings identified for costs of fresh water resources have been minimized from *21%* to *13%.*

6. Implementing the IWRM model under the free market conditions, industrial company gains:
   a) optimization of freshwater usage in technological processes;
   b) choice of optimal production modes;
   c) forecast of fresh water rates and wastewater quantities;
   d) compliance of the enterprise technological process with the EU legislation on wastewater treatment.

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2. Dvarioniene J., Knudsen, H.H, Stasiskienė, Z**.** *Pilot scale membrane filtration study on water reuse after reactive cotton dyeing*// Environmental research, engineering and management. ISSN 1392-1649. 2003, 3(25). Kaunas: Technologija. P 3-10.

Proceedings of international conferences:

1. Dvarioniene J. *Environmental performance improvement in tanneries: Lithuanian experience*// Euro Summer school – „Water and Resource Recovery in Industry“, Wageningen, The Netherlands, 2001.
2. Dvarioniene J. Possibilities of water resources saving in industrial companies // International conference for graduate students „Youth seeks advance 2003“, compendium of papers. ISBN 9955-9633-2-8. LŽŪU, Akademija, 2003. p. 246-251.
3. Dvarioniene J. *Closing water cycles in textile industry*// International conference „Sustainable Industrial Development: Product Oriented Strategies and Tools“. Conference‘s Reports Material (CD). Kaunas, 2003.

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Dvarioniene J., R. Zemaitaitiene, R. Klimaviciūte, A. Zemaitaitis. *Analyses of efficiency of chromium removal from wastewater with sodium aluminates and anionic flocculants in leather industry*// Environmental research, engineering and management. ISSN 1392-1649. 2001, 3(17). Kaunas: Technologija. P 11-19.

Patents:

Dvarioniene J., Kalvinskas V., Zemaitaitiene R., Klimaviciūte R., Zemaitaitis A. LR patent 4868. *Water composition for destabilization of dispersive systems and its abstraction.* OB biulletin. 2001. Nr.11.

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Reziumė

Darbo aktualumas

Lietuvai tapus pilnateise Europos Sąjungos nare, pramonės įmonėms tenka didžiulis uždavinys sprendžiant taršos mažinimo bei gamtos išteklių tausojimo klausimus. Pasikeitus rinkos ekonomikos sąlygoms, sugriežtėjus aplinkosauginiams reikalavimams, padidėjus vandens ir nuotekų kanalizavimo kaštams, vandens išteklių tausojimas tapo neišvengiama būtinybe visoms pramonės įmonėms. Gamtos išteklių naudojimo efektyvumo didinimas ir atliekų mažinimas bei jų racionalus tvarkymas ir antrinis panaudojimas yra vienas iš aktualiausių ne tik Lietuvos pramonės plėtros, bet ES prioritetų.

Lietuva, kaip ir kitos buvusio sovietinio bloko šalys, paveldėjo labai neefektyviai ir neracionaliai vandens ir kitus gamtos išteklius naudojantį ūkį ir, nepaisant per pastarąjį dešimtmetį pasiektos pažangos, apdirbamosios pramonės įmonės vis dar sunaudoja keletą kartų daugiau gamtinių išteklių BVP vienetui pagaminti nei vidutiniškai ES šalyse. Todėl šių įmonių neigiamas poveikis aplinkai yra palyginti stiprus, o konkurencingumas dėl didelės gaminių savikainos silpnas. Anksčiau įmonės nuotekų taršą “mažindavo” skiedimo būdu: švariu vandeniu mažindavo teršalų koncentracijas nuotekose ir taip išvengdavo mokesčių už taršą; šiandien tai *ne tik neracionalu, bet įmonėms ir ekonomiškai nenaudinga [Dvarionienė, Stasiškienė, 2001]*. Tuo tarpu naujoviškas nuotekų traktavimas siejamas su įmonės papildomais ištekliais; nuotekas būtina ne išleisti iš įmonės bet pakartotinai naudoti technologiniuose procesuose, kurti pakartotinio naudojimo, reciklo ir uždarų ciklų sistemas. Sėkmingo pakartotino nuotekų naudojimo, reciklo ar uždarų ciklų sukūrimo galimybes nulemia išankstinis vandens kokybės pokyčių numatymas, jų įtaka nuotekoms bei gaminamų produktų kokybei.

Vandens naudojimas yra viena iš plačiausiai Europos Sąjungos aplinkos apsaugos teisės aktais reguliuojamų sričių. 2000 m. ES įsigaliojusi *Bendroji vandens politikos direktyva* (*BVP, 2000/60/EC*) apibrėžė pagrindines subalansuoto vandens išteklių valdymo gaires, ypatingą dėmesį kreipiant į taršos šaltinius, iš kurių išleidžiamas užterštas vanduo. Remiantis šia direktyva, visos ES šalys privalo užtikrinti nustatytus vandens išteklių naudojimo bei apsaugos reikalavimus. Kita ypač svarbi pramonės įmonėms - *Integruotos taršos prevencijos ir kontrolės direktyva* (*TIPK, 96/61EEC*), pagal kurios nuostatas subalansuotam vandens išteklių valdymui užtikrinti būtina taikyti integruotas ir pažangias, ekonomiškai veiksmingas taršos prevencijos technologijas. Taip pat svarbus veiksnys, skatinantis įmones jau dabar ieškoti papildomų finansinių išteklių įmonės viduje, tai vandens ir nuotekų kanalizavimo kaštų išaugimas netolimoje ateityje, kuomet bus įgyvendinti *Miesto nuotekų valymo direktyvos (1991/271/EEB)* reikalavimai – atnaujinti nuotekų valymo įrenginiai. Manoma, kad ateityje Lietuvoje vandens tiekimo ir nuotekų kanalizavimo kaštai prilygs vidutiniams ES šalių kaštams, kurie šiuo metu 3-4 kartus didesni nei Lietuvoje. Siekiant atsieti ekonominį augimą nuo gamtos išteklių naudojimo ir pasiekti, kad išteklių naudojimas ir aplinkos teršimas augtų žymiai lėčiau nei gamyba ir paslaugos, *Nacionalinėje subalansuotos plėtros strategijoje* ypatingas dėmesys skiriamas gamybos ir paslaugų ***ekologinio efektyvumo*** didinimui.

Pagrindinis Lietuvos pramonės subalansuotos plėtros siekis formuluojamas taip – pagal ekonominio ir socialinio vystymosi bei išteklių naudojimo efektyvumo rodiklius iki 2020 metų pasiekti dabartinį Europos Sąjungos vidurkį, *pagal aplinkos taršos rodiklius – neviršyti ES leistinų normatyvų*, laikytis tarptautinių konvencijų, ribojančių aplinkos teršimą ir indėlį į globalinę klimato kaitą. Todėl gamtos išteklių naudojimo efektyvumo didinimas ir atliekų mažinimas bei jų racionalus tvarkymas bei antrinis panaudojimas yra vienas iš svarbiausių Lietuvos subalansuotos plėtros prioritetų.

Taigi neracionalus vandens panaudojimas (*ekonomine prasme*) ir neefektyvus taršos mažinimas bei gamtinių išteklių vartojimas pramonės įmonėse (*aplinkosaugine prasme*) paskatino atlikti mokslinius tyrimus vandens išteklių tausojimo ir nuotekų mažinimo srityje. *Šiuo nėra vandens išteklių tausojimo strategijų rengimo ir įgyvendinimo modelių, kuriuos naudojant būtų sudarytos prielaidos inovatyviai ir kryptingai pramonės įmonių veiklos plėtrai gamtinių išteklių tausojimo linkme.*

Tyrimo objektas – pramonės įmonių gamybiniai vandens ir nuotekų srautai.
Darbo tikslas – *įvertinus vandens išteklių vartojimo kriterijus, sukurti efektyvaus vandens išteklių integruoto valdymo pramonės įmonėje modelį ir patikrinti jo efektyvumą.*

***Šiam tikslui įgyvendinti išsikelti uždaviniai*:**

1. Išanalizuoti prevencinius vandens išteklių tausojimo ir nuotekų mažinimo metodus bei pažangias nuotekų regeneravimo technologijas.
2. Ištirti vandens išteklių sąnaudų efektyvumo didinimo galimybes Lietuvos pramonėje, atliekant atskirų pramonės šakų įmonių vandens sąnaudų lyginamąją analizę ir įvertinant pramonės įmonių vandens išteklių tausojimo potencialą.
3. Sukurti integruoto vandens išteklių valdymo įmonėje modelį.
4. Ištirti sukurto modelio taikymo efektyvumą pramonės įmonėse pagal matematiškai suformuluotus efektyvaus vandens išteklių vartojimo kriterijus.
5. Ištirti vandens reciklų ar uždarų ciklų kūrimo galimybes skirtingose pramonės įmonėse.
6. Atlikti nuotekų regeneravimo eksperimentinius tyrimus pramonės įmonėje ir įvertinti filtruotų nuotekų antrinio panaudojimo technologiniuose procesuose galimybes.

Tyrimo metodai

Darbas atliktas remiantis bendraisiais mokslinių tyrimų metodais: *sistemine analize, lyginamąja analize, masių balansu.* Vandens išteklių sąnaudų ir nuotekų mažinimo įvairiose Lietuvos pramonės įmonėse poreikio analizė atlikta naudojant apklausos rezultatus. Apklausai atlikti buvo sudaryti specialūs klausimynai, naudojant *anketinio tyrimo metodą*. Vandens išteklių tausojimo ir nuotekų mažinimo įmonėse nustatymui taikyti *procesų integravimo metodai*, vandens srautų analizė *(„WaterPinch“)*, taip pat *membraninės filtracijos tyrimo metodas.* Vandens srautų analizei taikyta duomenų apdorojimo sistema bei programinė įranga „*WaterDesign*“. Nuotekų kokybei tirti naudoti *cheminės analizės metodai.*

Mokslinis naujumas

Pagrindiniu darbo mokslinio naujumo elementu laikytinas pramonės įmonių integruoto vandens išteklių valdymo (IVIV) modelis, numatantis procesų integravimo ir pažangių nuotekų regeneravimo technologijų taikymo galimybes. Taip pat:

- vandens išteklių tausojimo galimybėms nustatyti taikytas sisteminis požiūris įmonės veiklos analizei, atskirų technologinių procesų įvertinimui, kurių pagalba galima ne tik užtikrinti vis griežtėjančius aplinkos apsaugos reikalavimus, bet ir tausojant vandens išteklius gaunama ekonominė nauda;

- sistemiškai įvertintos vandens sąnaudų mažinimo ir nuotekų antrinio panaudojimo, reciklų ar uždarų vandens ciklų kūrimo galimybės, integruojant nuotekų regeneravimo galimybes.

Teorinė ir praktinė darbo nauda

1. Įvertinti teoriniai vandens išteklių tausojimo ir nuotekų mažinimo tyrimo metodai, kaip pramonės įmonių subalansuoto vystymo strategijų teorinis pagrindas.
2. Numatytos procesų integravimo teorijos ir pažangių nuotekų regeneravimo technologijų taikymo galimybės rengiant ir įgyvendinant vandens išteklių valdymo modelį.
3. Sukurtas integruoto vandens išteklių valdymo modelis (IVIV) pramonės įmonėms, kurį naudodamos įmonės galės ne tik sumažinti vandens išteklių sąnaudas ir nuotekų kiekį, bet ir turės ekonominę naudą.
4. Išnagrinėtos ir įvertintos nuotekų antrinio panaudojimo, reciklų ar uždarų vandens ciklų galimybės, taikant IVIV modelį pramonės įmonėse.
5. Įvertinti tiesioginio vandens reciklo, nuotekų regeneravimo taikant membraninę filtraciją, filtruotų nuotekų naudojimo technologiniuose procesuose scenarijai.
6. Ištirtos vandens išteklių tausojimo galimybės, sietinos su Lietuvos pramonės įmonių inovatyvia ir kryptinga plėtra. Įvertintos atskirų pramonės šakų galimybės pakartotinai naudoti vandenį, kurti vandens reciklus bei uždarus vandens ciklus

Vandens išteklių tausojimo pramonėje moksliniai tyrimai autorės buvo atliekami eilę metų: pradedant nuo gamybinės veiklos, vėliau tęsiant įvairių Lietuvos pramonės šakų gamybinių nuotekų mokslinius tyrimus magistratūroje ir doktorantūroje. Doktorantūros studijų metu moksliniai tyrimai buvo atliekami bendradarbiaujant su Danijos technikos universiteto, CEVI centro (*angl. Center for Industrial Water Management*) mokslininkais, atliekančiais tyrimus vandens išteklių tausojimo pramonėje, ES mokslinių tyrimų ir eksperimentinės plėtros projekto *„Vandens sąnaudų mažinimas Europos tekstilės įmonėse naudojant inovatyvias plovimo ir vandens reciklo technologijas“* (*angl. Framework 5, “INNOWASH - Minimization of water consumption in European textile dyeing and printing industry using innovative washing and water recycling technologies*“), vykdyto 2001-2004 metais, rėmuose. Vandens išteklių tausojimo moksliniai tyrimai buvo atliekami įvairiose Lietuvos pramonės bei Vokietijos įmonėse, taikant procesų integravimo metodus, membraninės filtracijos tyrimai tekstilės įmonėje, nuotekų ir filtratų kokybinė analizė atlikta Denkendorfo tekstilės institute *(„Institut für Textilchemie ITC Denkendorf“)* Vokietijoje.

Mokslinio darbo rezultatų paskelbimas. Mokslinio darbo rezultatai paskelbti 5 publikacijose, iš kurių 2 straipsniai spausdinti recenzuojamuose žurnaluose, 3 straipsniai - tarptautinių mokslinių konferencijų medžiagoje.

Disertaciją sudaro įvadas, 5 skyriai - tyrimų apžvalga, darbo metodologija, tyrimų rezultatai, išvados, literatūros sąrašas (112 pavadinimų) ir priedai. Pagrindinė medžiaga išdėstyta 124 puslapiuose, įskaitant 28 lenteles ir 48 paveikslus.

Išvados

Atlikti tyrimai leidžia daryti šias bendrąsias išvadas:

1. Atliekant pramonės įmonių vandens išteklių sąnaudų lyginamąją analizę nustatyta, kad pagrindinis efektyvaus vandens išteklių sąnaudų kriterijus – vandens išteklių sąnaudos tenkančios produkcijos vienetui pagaminti (m^3/t, vnt., m). Lyginant su išsivysčiusių šalių pramonės įmonėmis ir GPGB rekomendacijomis, Lietuvos pramonės įmonėse produkcijos vienetui pagaminti sunaudojama *3-5 k.* (kartais 10 k.) daugiau vandens išteklių. Nustatyta, kad didžiausią potencialą vandens išteklių sąnaudų mažinimui turi *tekstilės, popieriaus ir kartono, metalų apdirbimo, chemijos ir maisto pramonės įmonės*.

2. Sukurtas integruoto vandens išteklių valdymo modelis *(IVIV)* padeda sistemiškai įvertinti įmonės vandens išteklių sąnaudas ir nuotekas. Naudojant šį modelį įmonėse galima kurti subalansuoto vandens išteklių *(tarp jų ir nuotekų)* valdymo scenarijus: visai įmonei ar atskiriems technologiniams procesams. Priklausomai nuo įmonės pobūdžio ir vidinių tikslų, atliekamas vandens srautų modeliavimas ir optimizavimas, atsižvelgiant į gamybos programą per tam tikrą laiką *(savaitę, mėnesį)* ir atsižvelgiant į efektyvaus vandens išteklių vartojimo kriterijus.

3. Atlikus IVIV modelio taikymo tyrimus nustatyta, kad išteklių valdymo efektyvumas priklauso nuo: gaminamos produkcijos apimčių, technologinių procesų specifikos, vandens tiekimo ir nuotekų kanalizavimo kaštų, teisinių reikalavimų, nuotekų regeneravimo ir atliekų tvarkymo kaštų. Nustatyta, kad taikant IVIV modelį didelėje tekstilės įmonėje, vandens išteklių sąnaudos *1t* produkcijos pagaminti būtų sumažintos *52%* - nuo *280* m^3/t iki *134* m^3/t. Mažoje tekstilės įmonėje vandens išteklių sąnaudos *1t* produkcijos pagaminti būtų sumažintos *62%* - nuo *113* m^3/t iki *39* m^3/t.

4. Nuotekų regeneravimo taikant membraninę filtraciją tyrimai pasirinktoje tekstilės įmonėje leidžia daryti išvadą, kad regeneruotos nuotekos gali būti naudojamos ne tik vandens reciklui ar uždaram ciklui kurti, bet ir kituose technologiniuose procesuose, t.y.:

- taikant membraninę filtraciją (*nanofiltraciją, reversinį osmosą*) tekstilės nuotekų regeneravimui, intensyvios nuotekų spalvos pašalinimo efektyvumas yra *95-100%*;
- nuotekų teršalų pašalinimo efektyvumas pagal ChDS ir savitąjį laidį yra *95%*, taikant NF ir *97%*, taikant RO membranas;
- įmonė, įdiegusi plovimo nuotekų uždarą ciklą per metus sutaupytų *86%* vandens sąnaudų bendrųjų kaštų tolydinėje plovimo linijoje arba nuo *35* m^3/t sumažintų iki *5,1* m^3/t.

5. Taikant IVIV modelį nustatyta, kad po modelio pritaikymo tiriamoje tekstilės įmonėje vandens kaštai sumažėjo nuo *21%* iki *13%*. Įvertinus tai, kad įmonė per metus sunaudoja apie 800 000 m^3 vandens išteklių, pasiektas *8%* ekonominis efektas yra pakankamai ženklus įmonei.

6. Nustatyta, kad taikant integruotą vandens išteklių valdymo *(IVIV)* modelį, sudaromos prielaidos inovatyviam ir kryptingam pramonės įmonių veiklos vystymui gamtinių išteklių tausojimo linkme bei didinamas įmonių ekonominis efektyvumas. Rinkos sąlygomis pritaikius modelį įmonėje būtų galima užtikrinti šiuos svarbius aspektus:

a) vandens sąnaudų optimizavimą technologiniuose procesuose;
b) optimalių gamybos režimų parinkimą;
c) vandens sąnaudų ir nuotekų kiekių prognozavimą;
d) su vandens išteklių vartojimu susijusių kaštų prognozavimą;
e) su nuotekų tvarkymu susijusių aplinkos apsaugos reikalavimų atitiktį.

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