2019b; 2020]. This forms a long-term trend of growing earth's surface average temperature and the frequency and amplitude of abnormal climatic events, such as floods and droughts, catastrophic showers, and storms, which have an ever stronger physical impact on the energy sector.

Based on the above, the main impact of thermal energy on climate change is heat dissipation. The improvement of the latter can be the main factor in combating climate change.

A significant amount of scientific work is devoted to the problem of finding effective ways to utilise low-potential heat [Balghouthia *et al.* 2005; Dalampakis *et al.* 2017; Dudnik *et al.* 2020; Korobiichuk *et al.* 2019; Kumar Agrawal *et al.* 2019]. The main argument against the use of circulating hot water from nuclear and thermal power plants is its relatively low temperature, despite a significant thermal potential.

It should be noted that studies into the efficiency of soil heating with waste warm water have been conducted in the United States, France, Germany, Bulgaria, Russia and other countries [Babich *et al.* 2017; Balghouthia *et al.* 2005; Issakhov 2014; Korobiichuk *et al.* 2019; Madden *et al.* 2013; Prats *et al.* 2012; Rakovec *et al.* 1988; Vostrikov 2015].

As an alternative, waste heat from industries can be utilised by heat and reclamation systems that enable the use of waste hot water to increase agricultural production.

MATERIALS AND METHODS

The research program envisaged systematic monitoring of soil and air temperature, water temperature in the heating system, soil moisture, precipitation, agrochemical properties of soils, and yields of perennial grasses. The soil temperature was measured from a depth of 0.00 m to 1.00 m every 0.10 m, and further to 2.00 m every 0.50 m, both in and between pipe joints. Measurements were carried out once a day at 13:00 using TM-10 exhaust thermometers. The study of the soil water regime was carried out by systematic observations of precipitation and soil moisture to the depth of 1.00 m.

The amount of heat dissipated in the soil was determined by measurements of water temperature at the inlet and outlet and it was calculated using the following formula:

$$q = \frac{Q \cdot C \cdot (T_n - T_k)}{F} \tag{1}$$

where: q = heat transfer per unit area ($W \cdot m^{-2}$), Q = water flow in the pipeline ($m^3 \cdot s^{-1}$), C = water capacity ($J \cdot m^{-3} \cdot °C^{-1}$), T_n, T_k = water temperature at the entrance to the system and at the exit (°C), F = area of the heating system (m^2).

An alternative system for the utilisation of wastewater heat from energy facilities is shown in Figure 1.

The technology of ground heating is implemented using a system of pipelines (heaters) with the diameter of up to 50 mm, which are placed into the ground at the depth of 0.50–0.60 m spaced every 1.00–1.50 m. Water which passes has temperature of 25–38°C. Heaters of 50 m in length are connected on one side to the distribution pipeline of 100 mm in diameter and 12–17 m in length, and on the other side – to the collecting pipeline of the same diameter and length to form a "battery". The ground heating area was about 600–850 m^2 depending on the distance between the heaters. The research involved several schemes: control (unheated field), ground heating with b = 1.00 m, and ground heating with b = 1.50 m, where b is the distance between the pipelines.

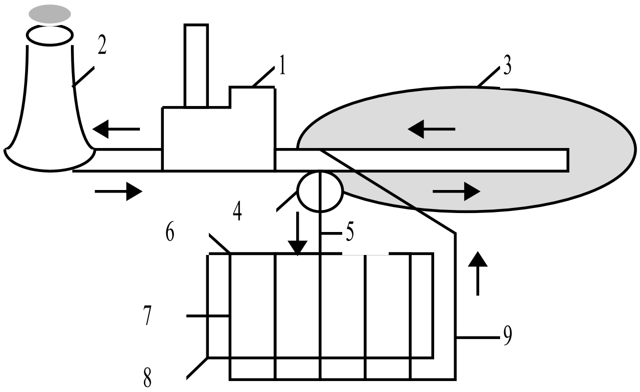

Fig. 1. An alternative system for the utilisation of wastewater heat from energy facilities: *1* = energy enterprise; *2* = cooling tower; *3* = pound cooler; *4* = heat reclamation system and pumping station; *5* = supply pipeline; *6* = distribution pipeline; *7* = cooling pipeline; *8* = assembly pipeline; *9* = branch pipeline; source: own elaboration

To study the processes of water cooling during the movement through pipelines, as well as heat dissipation into the ground, 50 mm pipes are placed according to the "snake" scheme with the distance between pipes of 1.00 m and 1.50 m. The overall length of the pipeline is 600 m. The flow of water in the pipelines is regulated by valves installed in the control wells and measured by flow meters.

Parameters of the heated network (diameter of pipes, depth of laying, distance between pipes) are chosen based on the need to maintain uniform heating of the soil root layer, efficient water cooling, and the preservation of pipelines during tillage.

Water velocity in the pipes and the depth of the pipes are determined by thermal calculations which show that the velocity of water in the pipelines should be in the range of 0.15–0.25 $m \cdot s^{-1}$, distance between the pipes of 1.00–2.00 m, and the depth of pipes not more than 1.00 m, as the thermal resistance of the soil increases with depth.

The experimental research of surface heating has been conducted in Western Ukraine, in particular in the Rivne Region with two large Nuclear Power Plants (Ukr. Rivne Nuclear Power Plant and Khmelnytskyi Nuclear Power Plant) – Figure 2.

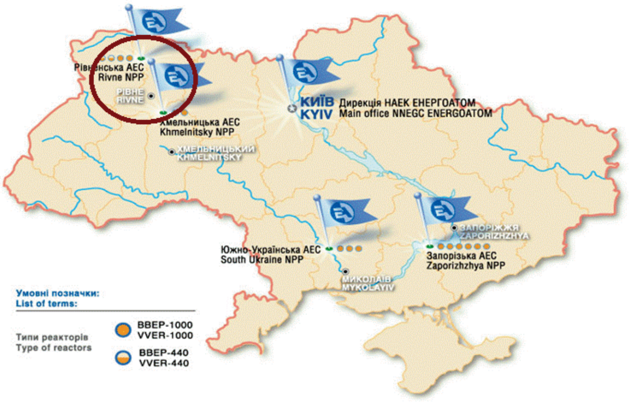

Fig. 2. Location of the research area; source: own elaboration

RESULTS AND DISCUSSION

One of the ways to use waste hot water is thermal reclamation, which is implemented with the help of low thermal water pollution of open ground and growth of agricultural crops.

The research involved the system of ground heating of light-medium humus black soils in the central forest-steppe zone in years that differ in climatic conditions, such as heat and precipitation (Tab. 1).

The aggregate air temperature during the growing season consists of average daily air temperatures from April to October.

The analysis of meteorological conditions in particular years (Tab. 1) allowed us to provide a wide-range study on the effect and efficiency of ground heating and humidification by waste-water.

In areas with underground heating, the heat source in addition to solar radiation provides the flow of heat from the pipes in the ground, which circulate warm water.

In this case, the soil temperature regime of depends on the depth of pipes, coolant temperature, soil moisture, etc. and it has a complex temperature distribution in the soil profile (Figs. 3, 4).

Warm water that passes through the system of pipes creates an artificial linear heat source. This contributes to significant thermal gradients that show a radial distribution from the axis of the pipe. The presence of such temperature gradients in the soil determines the complex nature of isotherms: wavy in the upper and lower horizons and elliptical near the pipe. The largest increase into the soil temperature is observed in the area of the pipes, but at different times of the year, the formation of temperature fields vary (Fig. 3).

Table 1. Heat and moisture in particular years of different climatic conditions

Year	Heat supply			Moisture supply			
	total air temperature during growing season (°C)	average temperature (°C)		precipitation of the year (mm)	characteristics of the growing season	precipitation in the growing season (mm)	characteristics of the growing season
		year	growing season				
1	2748	5.3	15.0	625.3	humid	414.7	very humid
2	3000	8.6	16.4	511.4	dry	309.1	dry
3	2550	3.7	13.5	438.5	very dry	261.7	very dry
4	2846	7.4	15.5	661.9	humid	409.2	very humid

Source: own study.

The ground in the study area is genetically homogeneous. To some extent, the spatial mosaic is manifested by the presence of minor micro-depressions.

The characteristics of moisture and physical properties of the soils are shown in Table 2.

Table 2. Moisture and physical properties of soils

Horizon (cm)	Density ($g\cdot m^{-3}$)	Volumetric mass ($Mg\cdot m^{-3}$)	Total porosity (%)	Moisture content (% by weight of dry soil)	
				total	least
0–20	2.46	1.34	45.5	35.72	29.73
20–40	2.47	1.29	47.8	33.25	26.44
40–60	2.50	1.33	46.8	30.17	24.47
60–80	2.57	1.43	44.4	28.56	23.01
80–100	2.57	1.44	44.0	27.81	22.17

Source: own study.

The temperature regime of soils is formed under the influence of atmospheric climate. However, various agronomic measures also affect the thermal and water-air regimes of soils, thereby causing the course of various soil processes. Such agronomic techniques include heating of the ground with artificial heat sources. The main source of heat that enters the ground in unheated areas is solar radiation which is absorbed by the upper layers and then transferred to deeper soil zones.

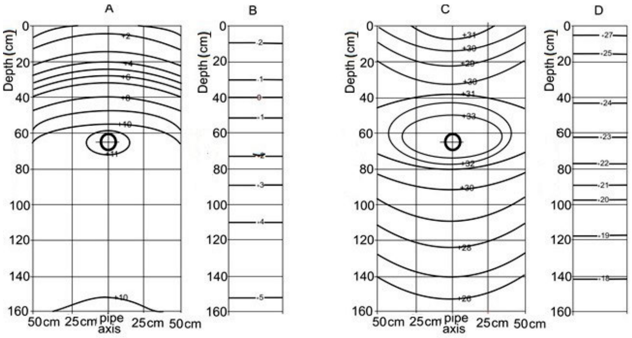

Fig. 3. The distribution of temperature in the soil profile at different times of the year: A) ground heating with the distance between heaters of 1.0 m (winter), B) control (winter), C) ground heating with the distance between heaters of 1.0 m (summer), D) control (summer); source: own study

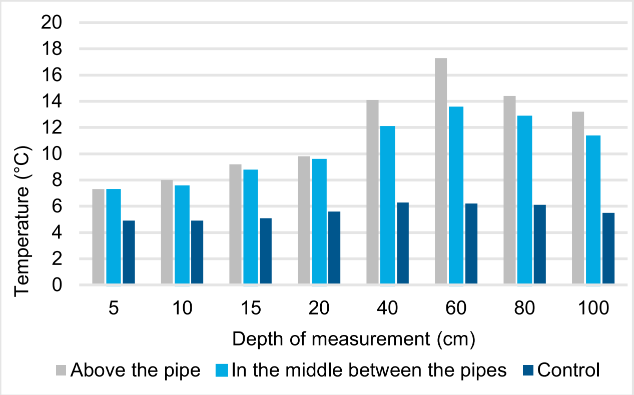

Fig. 4. The average monthly temperature (°C) of the soil profile in the conditions of heating in April; source: own study

As we can see in Figure 3A and B, in winter, the soil temperature at all research sites, including the control one, is higher than the ambient air temperature, and the heat flow is directed from lower soil layers to the surface and the thermogradients are positive. Their values are insignificant and for December average values are 4.5°C·m^{-1}. In heated areas, the constant supply of heat increases the heat flow from the depth of the soil profile to its surface. The upper 0–60 cm layer creates a zone with a high-temperature gradient, the value of which is 15–16°C·m^{-1}. Ascending heat flows from the heater system create a shield against the penetration of negative temperatures into the soil. Below the heater system, there are downward heat fluxes. But since the heat dissipation into deeper horizons is insignificant, the value of thermogradients in the layer of 60–160 cm is negligible.

In summer, during the control period (Fig. 3D), when ground heating reaches maximum values due to solar activity, the heat flow is directed from the surface to deeper layers of the soil profile. The value of the vertical thermal gradients for the layer 0–160 cm is 5.6–6.0°C·m^{-1}.

Along with the heat coming from solar radiation, heat also comes from the system of linear heaters, which causes the formation of more complex temperature fields in the soil. The soil temperature of the upper 0–20 cm layer is more affected by solar radiation and the heat flow is downward directed. In a deeper layer of 20–60 cm, the temperature is more influenced by the ascending temperature flow from the heating pipes (Fig. 3C).

Thus, in the soil heated profile, it is possible to distinguish two zones of raised temperatures, at the soil surface and the zone of pipe heaters.

At the depth of 5 cm, the maximum temperature effect is observed in March (5.3°C) and in February (slightly less than 4.6°C). The minimum effect of heating is observed in August–September (1.3–1.6°C). The sums of active temperatures in the arable layer of the soil increase by 156.3–680.5°C, which is 20–25% higher than in the unheated area.

The studies have shown that the heating system increases the temperature of the soil root layer by 2–8°C and the surface air zone by 0.2–1.2°C, depending on the state of vegetation. The soil temperature of 5°C, which indicates the restoration of vegetation of most crops, occurs in warmed soil 15–18 days earlier in spring, and in autumn the soil cools down 6–8 days longer. The advance in the onset of temperature at 10°C in the upper arable layer is 8–10 days. The sum of active temperatures for April–October in 10 cm soil layer increases by 375–573°C, and at the depth of 40 cm by 970–1200°C. Thus, heating of the soil allows to extend the crop growing season by an average of 3–4 weeks.

It is worth noting that the thermal effect changes over time. The reason for this is the constant change of climatic conditions and water temperature in the heating system.

Annual fluctuations in the soil temperature, both in heated areas and in the control area, are characterised by significant amplitude and depth of penetration. The temperature regime during the year has two periods: heating and cooling. Their duration is primarily affected by air temperature, precipitation, and the nature of vegetation (Fig. 5).

As a result of rising air temperatures in February–March, about the end of March and the beginning of April, the soil in the control area warms up. By the beginning of May, the temperature of the arable layer exceeds 5°C. It is worth noting that the spring warming of the soil in particular years of different meteorological characteristics is observed at different times. Thus, in the years under research, the temperature of the arable layer was heated to 5°C at the earliest in 11–13.04, at the latest in 03–08.05. The highest soil temperatures were observed in summer months (July), during a period of the highest air temperatures. For most of the growing season, the temperature of the soil root layer did not exceed 20°C. Only in particularly warm periods, the temperature of the upper 15 cm layer exceeded 25°C. The decrease in soil temperature in the control area begins in September. The transition through 10°C, and hence the end of

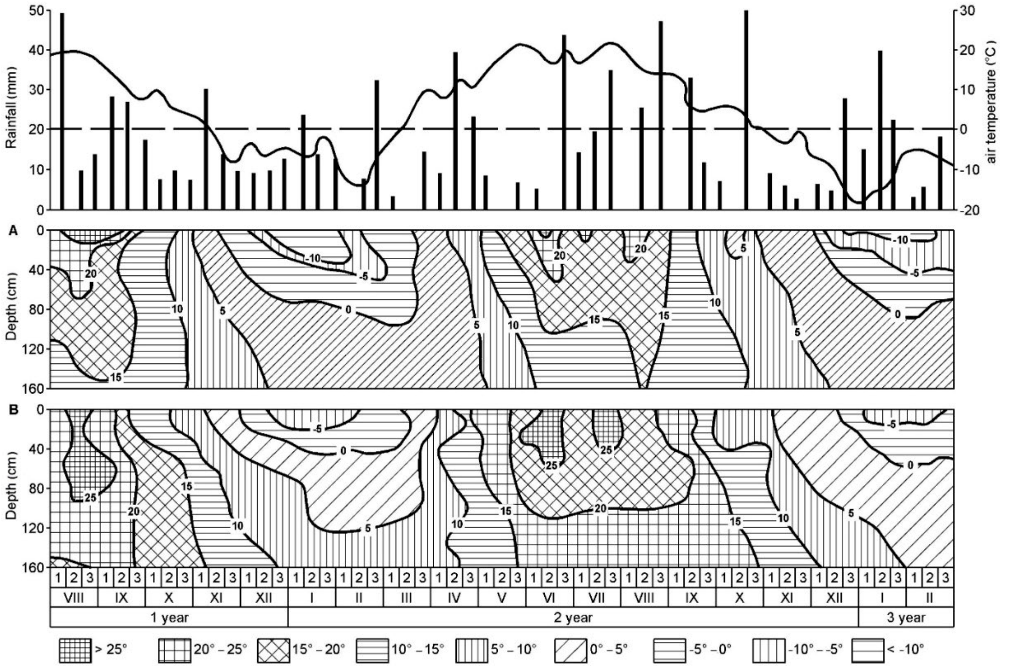

Fig. 5. Thermoisoplets of soil at research areas: A) control, B) heated soil (distance between pipes is 1.0 m); source: own study

active vegetation of plants, occurs in the period from the last decade of September to the first decade of October, and below 5°C in late October-early November.

With a further decrease in air temperature in December, the soil begins to freeze. The thickness of the frozen layer and the magnitude of negative temperatures vary depending on the severity of winter. During the study period, negative temperatures reached the depth of 1 m, and in the upper 10 cm layer, the temperature dropped below −10°C. In mild winters, the depth of freezing did not exceed 50 cm, and the soil temperature was above −5°C (Fig. 5).

The supply of heat to the soil from the heating system leads to a shift in the onset of characteristic temperatures, as well as to changes in the duration of the periods of heating and cooling. In spring, temperatures above 5°C occur in late March and early April, and in some years in late February, which is 25–45 days earlier than in the control area. In the second or third decades of April in the heated areas, the soil temperature at a depth of 20 cm passes through 10°C, which allows 20–25 days earlier to start growing crops. At the same time, the depth of penetration of positive temperatures increases in the heated areas. During the years of observations, the temperature of 20°C reached a depth of 110–200 cm, while in the control this temperature did not exceed 50 cm. In summer, the heated soil temperature was maintained in the range of 20–30°C. This temperature range is optimal for the growth and development of most crops.

In the autumn, the decrease in temperature in the heated areas occurs later than in the control. The temperature transition through 5°C occurs in the first or second decades of November, which is 8–12 days later than in the control.

The beginning and end of the growing season for most crops is the transition of soil temperature through 10°C. Observations have shown that at heated areas the transition of soil temperature through 10°C in spring occurs 20–30 days earlier and 16–26 days later in autumn than in the control area. Thus, in general, the growing season is extended by 36–56 days. The prolongation of the growing season leads to the accumulation of more heat in the soil, and increase in the number of active temperatures. The sum of active temperatures in April–October in the 10 cm layer of soil increases by 375–573°C, and at the depth of 40 cm by 970–1200°C.

According to the studies, heat radiation from the soil occurred during the entire period of observation. The value of the total heat flow from the soil at a distance between linear heat sources of 1.0 m is 0.320–0.370 kcal·cm^{-2}·min. In this case, only the upper layers of the soil (0–20 cm) take part in heat exchange.

On the one hand, such systems allow to optimise conditions for growing crops, and on the other, to return chilled water in the ground for reuse.

The soil heating system (Fig. 1) provides stable cooling of water from energy companies by 5–10°C with a specific heat output from 10 to 25 W·m^{-2} during the year.

Changes in the thermal regime of the heated soil cause changes in the formation of the water regime. These are manifested mainly in the redistribution and accumulation of moisture in the soil profile.

The use of irrigation with waste warm water in the context of ground heating is interesting, and it is possible to distinguish two aspects, the effect of insulated irrigation on soil temperature and changes in irrigation water temperature during the process.

It should be noted that during sprinkling, droplets in the air are exposed to two processes: air temperature above the irrigation water temperature heats droplets and droplets are cooled by evaporation water. When the air temperature is below the temperature of irrigation water, which almost always has been observed, droplets are exposed to cooling only (Tab. 3).

The change in water temperature during irrigation depends on water temperature, air temperature, and wind speed. As can be seen from the results of the research, the wind speed is of paramount importance, because once it increases the heat consumption for evaporation increases sharply, which significantly lowers the temperature of irrigation water. The decrease in air temperature from 25.7 to 24.1°C and water temperature from 37.6 to 32°C at almost constant wind speed (0.90–1.00 m·s^{-1}) does not lead to a significant decrease in droplet temperature.

In this case, short-jet nozzles were used for sprinkling, so the exposure of droplets to atmospheric factors was short. It is clear that with increasing the trajectory of droplets, their temperature may differ from our results, so this must be taken into account when using longer range sprinklers and devices.

While analysing the cooling depth of irrigation water from the nozzle to the edge of the humidification circuit, it can be noted that the largest cooling effect occurs at a distance of 2–3 m from the nozzle. This is due to the fact that small droplets fall in this area and lose their heat faster. At the same time, along with the nozzle, the temperature of small droplets changes slightly due to a certain microclimate in this area and the short exposure of droplets to external climatic factors. On average, the temperature of irrigation water decreases during sprinkling by more than

Table 3. Irrigation water temperature during sprinkling

Water temperature at sprinkler nozzle (°C)	Air temperature (°C)	Distance from sprinkler nozzle (m)					Wind speed (m·s^{-1})
		1	2	3	4	5	
37.6	25.7	26.6	25.1	27.0	27.0	26.7	0.9
38.8	27.6	26.8	25.9	26.8	26.9	26.4	1.2
38.5	25.7	25.5	25.3	25.4	25.5	25.4	2.2
38.4	26.6	24.8	23.8	24.6	25.7	25.6	3.0
32.0	24.1	25.0	24.8	25.0	26.8	26.5	1.0

Source: own study.

10°C. As the wind speed increases, the cooling of the water increases up to 15°C.

Irrigation with warm water also leads to changes in soil temperature and this effect has its own characteristics. To date, this issue is virtually unexplored.

CONCLUSIONS

The results of our research showed that at the heated areas the transition of soil temperature through 10°C in spring occurs 20–30 days earlier and 16–26 days later in autumn than in the control area. Thus, in general, the growing season increases by 36–56 days. Prolongation of the growing season leads to the accumulation of more heat in the soil and increase in the number of active temperatures.

The irrigation (without heating) with water of 35–38°C does not lead to an increase or a significant decrease in its temperature compared to water of normal temperature used for the irrigation (22–25°C). In our opinion, it is due to the fact that when water hits the surface of soil, it loses much of its heat and differs a little in this respect from ordinary irrigation water. Thus, as a result of watering at a depth of 5 cm, the soil temperature decreased by only 0.5°C, while in areas without irrigation, the temperature during the same time decreased by 1.0°C. This means that a certain amount of heat entered the soil with irrigation water. Therefore, for almost a day the soil remained slightly warmer (0.2–1.0°C) at the depth concerned. On the contrary, from 10 cm and to 40 cm in depth, watering led to an increase in soil temperature by an average of 0.3–0.8°C.

As for the heated areas, the effect of irrigation with warm water has its own characteristics. Thus, the cooling depth of the 5 cm soil layer exposed to heating and irrigation increases its temperature by 1.3°C. At the same time, on the heated sites temperature decreases on the depth up to 40 cm. Thus, warm irrigation water causes the accumulation of insignificant heat which is quickly lost.

It follows that the heating system increases the temperature of the soil, whereas irrigation with warm water does the same to a lesser extent. When these are used in combination, it allows us to control both temperature, water–air, and other modes.

As a result of the underground heating application in the root layer and the surface layer of air, there is a change in the whole range of processes that affect growth, development, and formation of crop yields. The optimisation of soil temperature and water–air regimes accelerates the growth and development of crops and, accordingly, increases their yield. It is known that crop yields are a criterion for assessing the effectiveness of various measures, including thermal reclamation.

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