STATE OF SEAWATER INTRUSION OF THE CROATIAN COAST

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ABSTRACT

Croatia is a typical Mediterranean country with very long coastal area and more than thousand islands on the eastern part of Adriatic sea from Istria peninsula on the north and Dubrovnik area on south. This is the part of Dinarc karst region mainly built from karsti - fied carbonate rocks. Due to the sea level changes in Quarternary it is characterisied by deep karstification what enable on many places very distant sea water intrusion forming labile balance of fresh and salt water in karst underground. In this paper will be present the general situation along the coast and islands, research methodologies used, and man - agement which is more and more acceptable solution for fresh water exploitation in this region.

INRODUCTION

Croatia is the country with more than thousand islands and several thousand kilometers of coastline, which is the exceptional advantage for the country during the development planning and which is also the big problem for the water supply organization due to sea influence on the coastal fresh water systems. The coastal zone is very indented with various morphological shapes, from relatively flattened coast in the Istrian peninsula and Ravni Kotari to predominantly steep rocky coast especially distinguished in the foot of the biggest Croatian mountain Velebit that has almost unbroken spreading along 150 km. The part of the coast built of flysch clastic deposits has long beaches, especially distinguished in Dalmatia between Split and Neretva river valley. The coastal zone and the islands are predominantly rocky so the sea influence through karstic coastal aquifers is exceptionally high.

The coastal area is locally densely inhabited with the greatest population concentrations in the big cities of Rijeka (200.000) and Split (250.000), but in the other cities and settlements as well (Pula, Zadar, Šibenik, Makarska, Dubrovnik). The islands are much less inhabited; the cities have up to 5000 inhabitants (Krk, Mali Lošinj, Rab, Pag, Hvar, Korćula). Generally it could be said that around one million inhabitants live in the coastal area, especially if the cities and settlements in the immediate hinterland are added to the cities on the coast, which are oriented towards the mentioned centers. In the summer, due to incoming tourists the number of inhabitants is doubled and it is than that huge problems emerge in providing with the normal water supply, the waste disposal, the waste water treatment and in road traffic, because the number of cars is multiply increased. For decades, the islands have the trend of decrease of inhabitants, so some small distant islands are left almost without people. The highway that connects inner part and tourist developed coastal part is under construction, which is expected to increase the number of tourists.

The industry is mainly connected to the big cities (Rijeka, Split, Pula, Zadar, Šibenik, Ploće), which are as well the harbors for merchandise transport towards the central Europe and Bosnia and Herzegovina. The industrial production is mostly highly decreasing so the numerous industries stopped with the production, which is good for environment, but not good for population. In the area of Rijeka there is the big oil refinery, harbor and oil pipeline towards the inland and towards Yugoslavia and Hungary. The shipbuilding is also connected to big cities and it is mostly in recession as well as everywhere else in Europe. The agriculture (vegetables and fruits) is developed in Istrian peninsula, surroundings of Split and valley of Neretva river, however the wine culture and production is developed in the whole coastal region and on the bigger islands with numerous original protected grape sorts. Similar situation is with the olive culture and production of olive oil. The tourism is the most significant activity in coastal region. Numerous hotels, houses and restaurants offer the tourists great variety of activities, which together with the natural beauties of coastline are becoming more attractive to the tourists from European and oversea countries from day to day. Dubrovnik should be singled out as the most preserved living middle age city that is visited by numerous tourists, and there is Split (Dioklecian palace) as well as the other cities on the coast. It should be emphasized that in the coastal region three national parks have been established (Mljet, Kornati and Krka), which accept numerous visitors. About 30 km from the coast there is the National park "Plitvice Lakes".

The main problems in coastal region concerning the communal activities are how to ensure the drinking water to periodically high number of inhabitants, especially on the islands, how to treat the waste waters and communal waste. The preparations for constructing great number of waste waters purification devices is in progress, as well as the changing of "wild" disposal sites into sanitary disposal sites, the reconstruction of peak consumption in water supply by

means of water catchment reconstructions and better management of water systems, the reorganization of water supply on the islands. The problems are periodical intrusions of salt water into coastal aquifers, the aquifer protection, because of the fast spreading of the cities and building of highways. Lots of problems are in keeping the natural systems in acceptable frames of sustainable development. It is emphasized that the water supply springs and aquifers are for now in very good condition and the water is completely within the drinking water standards and some of the springs are planed to be used for water bottling.

GEOLOGY

The coastal region of Croatia belongs in the whole to megastructural unit of Dinarides, which has all the characteristics of carbonate platform, whose forming started at the end of Paleozoic age, the main sedimentary evolution is during Mesozoic age and it mainly finishes its development during Tertiary age. Carbonate rocks (limestones, dolomites) are absolutely predominant, tectonically very disturbed, which reached high karstification level during the Quaternary age. The strike of Dinarides is generally northwest-southeast, almost parallel to coastline. The complexity of the Dinarides structure is connected to the influence of the subduction zone of African plate under European plate, so the emergences of multiple thrusting and differential movements of tectonical units in regard to changes in stress direction are frequent. The mutual relations between structural zones of Dinaric platform - "Dinarik" and Adriatic carbonate platform - "Adrijatik" (Herak, 1986, 1991) are significant for the coastal region. Other opinions exist, that speak of unique carbonate platform and disintegration of that plate after finishing the sedimentation cycle. It is important to emphasize the spreading of Dinarides into Adriatic space, which comprises all the islands and it is presumed that there exists the alochtone relation regarding the Apulian structure. In any case it is important to emphasize that the whole coastal region and the islands belong to Dinarides and the contact of "Dinarik" (High karst) and "Adrijatik" is significant for the development of the coastal region. That contact zone mostly spreads in coastal zone and somewhere it protrudes deeper in the inland and then the flattened coastal areas are significantly widening. Water impermeable clastic rocks are of Paleozoic and Tertiary age and while the Paleozoic ones build the barriers for the groundwater movement in the zones of watersheds of wide spreading karst catchment areas, the Tertiary ones built the barriers in the outflow zones in coastal region. Therefore, the aquifers are deeply karstified carbonate rocks (limestones and dolomites) and the barriers are mentioned clastic rocks.

CHARACTERISATION OF COASTAL AQUIFERS

The coastal aquifers of Adriatic region in Croatia belong in the whole to the group of karst carbonate aquifers with very small rate of intergranular aquifers in the valley of Neretva river, but in that area the main water dynamic is connected to karst underground as well. It is important to emphasize that they are so called geosyncline type of karst aquifers, which are different from the basin type (Paris basin) exceptionally tectonically disturbed with very deep karstification, which because of the youngest tectonic movements sometimes reach several hundreds of meters below the present sea level.

The main characteristic of coastal karst aquifers in Croatia is the existence of big karst springs (up to 200 m^3/s) with considerable amplitudes in outflow depending on the season precipitation rate, so some of the big karst springs in the summer period completely lack the outflow. The karst relief is developed in its characteristic unity up to the level of big karst poljes so the multiple outflows from the karst aquifer on different levels within one catchment area are not rare. For the coastal aquifers it is important to say, that besides the coastal springs there are numerous submarine

springs, which point to specific genesis of the whole coastal and island karst region in Croatia. Thus, it is important to emphasize the changes in sea level during the Quaternary age, when the present karst system was formed. The previous investigations showed that the sea level in the beginning of Quaternary age was at least hundred meters lower than today's one (Šegota, 1968) and the karstification processes were directed towards those levels. With gradually elevation of the sea level, especially after the last glacial, the level of specifically lighter fresh water system was elevated. Former places of natural springs are sunk in the sea and these are today's submarine springs, but what is especially important to emphasize is that the salt sea water entered the deeper parts of coastal karst aquifers, so today's fresh water dynamics takes place in the conditions of the labile equilibrium of fresh and salt water in the karst underground. How much it is spread in the coastal region in Croatia is best shown in the figure 1, from which it is obvious, that the majority of coastal aquifers and almost all island coastal aquifers are under the active sea influence. The sea influence in the parts of coastal region reaches dozens of kilometers in the inland and the island aquifers are mostly limited due to the deep sea intrusions.

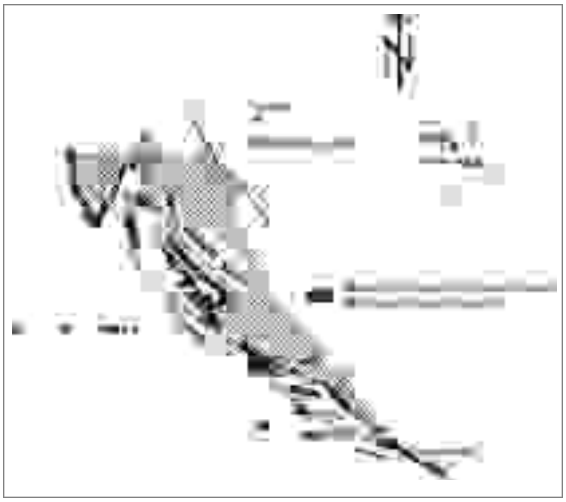

Figure 1. Sea influence on costal aquifers (Biondić, B. et al., 2000).

Regarding that it is the question of the very heterogeneous karst aquifers, it is hard to evaluate the average hydraulic parameters, but it is important to emphasize that it is the matter of very fast groundflows, which in some areas reach the values greater than 30 cm/s, directed along high fractured and karstified zones within the carbonate massif. The karstification of carbonate rocks opens the channels of cave dimensions so the emergences of real underground rivers are known in the aquifers. The thickness of the carbonate mass doesn't represent the thickness of the aquifer at the same time, because sometimes the thickness of the carbonate mass is ten thousand meters, but in the coastal region the karstification depth is significant, which mostly doesn't exceed 150 m, and the most often case is that the most active groundflows have the depth of 50-100 m below sea level. The contacts of the sea with so-called old sea water are at the same depth in the deep parts of aquifer, which due to tectonic sometimes reach the depth of 300 m below sea level. Retention capabilities of coastal karst aquifers are relatively small, which is expressed as significant decrease of karst spring discharge during the summer period. Therefore, when the spring discharges are the smallest, the water needs are the biggest and that is the main problem of Adriatic coastal region in Croatia.

The exploitation of coastal groundwater resources is connected to the relation between needs and natural capabilities. Today in the Adriatic catchment area, around 8.5 m^3/s of water is in exploitation. This value is connected to summer dry periods, when the level of needs is the highest. The highest degree of exploitation is in the areas of two major cities (Rijeka, Split), but the other cities and tourist centers in the coastal area as well, and the lowest degree is on the islands, where the resources are limited. Only two islands have independent water supply. These are the island of Cres in the northern part of Adriatic, where the water is pumped from Vrana lake, the fresh water mass with around 220 Mm^3 and the island of Vis, the furthest island in the southern part of Adriatic, where the possibilities are limit-

ed, but still satisfactory in regard to the needs of inhabitants and tourists (around 20 l/s). The big islands are completely or partially connected to mainland water resources by means of underground pipelines, and for the small island the solutions with desalinization of brackish water from local resources are in the process. The problem is the constant increase of water needs and the exploitation in the conditions of open sea influence on the coastal aquifers. This is evident on many places along the coast, however the solutions of satisfying the peak consumption of drinking water during the dry summer period lay in the regional connecting of the distribution nets and in using the water from permanent river waterflows (Zrmanja, Krka, Cetina). The danger for the coastal aquifers lays in possible global climate changes and in the expected increase of the sea level, but for now, there are no firm evidence although the problems of salinization in coastal aquifers are more frequent. It is important to say that coastal aquifers in coastal region of Croatia have the renewal reserves in season cycles and there are no permanent effects of over pumping.

The role of coastal karst aquifers in the development of coastal region is immeasurable, because these are the only water resources in this region and the whole development depends on protection and correct exploitation of such water resources. Regarding the today's limiting exploitation conditions the future solutions are considered and investigated, which are the limited over pumping of aquifers combined with artificial recharge from the accumulated high water waves, the exploitation of water from artificial accumulations and the water transfer from distant big karst springs, which gained the status of strategic reserves for future development of coastal region. It is important to mention that despite the high vulnerability of karst aquifers the waters are of good quality and big attention is given to protection, especially during the construction of major infrastructure objects (highways).

The investigation methods of karst aquifers are in accordance with the European standards. That could be owed to the active participation of Croatian experts in COST 65 and 621 European Union projects, but as well to cooperation with numerous institutions in Europe and USA. Together with classic hydrogeological and hydrological methods, the modern hydrogeochemistry analysis and modelling are used, which is very significant for prognosis in coastal region and for wide range of direct measurements of dynamic changes in aquifers. The users are increasingly turning towards the management of coastal systems and decreasingly towards conventional and very expensive technical solutions (grouting curtains, membranes, dams, etc.). It should be emphasized that in the coastal region in Croatia numerous technical objects were constructed with various success. In the area of Rijeka, by building of water catchment gallery and rebuilding the greatest natural spring catchment, the exploitation quantities of water are doubled, which provided city of Rijeka with one of the most stabile water supply system in the whole coastal region and the investigations for new catchment constructions outside the sea influence are in the progress. The constructed grouting curtains in the whole coastal region didn't give satisfying results, although they have still not been rejected as the possible solution, where the natural conditions are favorable. In the Istria region the system of artificial recharge of biggest karst spring Gradole was successfully built, because the water for the peek consumption is used by direct purification from the accumulation. On the small islands nowadays the local aquifers are investigated and the new systems for desalinization of brackish water are introduced (Lastovo, Mljet, Susak, Unije, etc.).

CURRENT STATE OF SEAWATER INTRUSION

In evaluation the influence of sea water intrusion on the karst aquifers in the region of Adriatic Sea in Croatia two basic types should be distinguished - the influence on the mainland and on the island coastal aquifers. The differences lay in the possibilities of renewal the fresh water

reserves. While the mainland coastal aquifers are connected to big karst catchment areas with the mountain chains rich with precipitation by the coastline, the island aquifers have the limited recharge areas. The consequences are the different shapes of dynamic behavior of aquifers. In the mainland coastal aquifers the problems of the sea influence are connected only to long dry summer periods, while on the islands this is the permanent problem.

The basic characteristics of karst aquifers are high velocities of groundflows and low retention capability, which have the consequence of high outflow range in different hydrological conditions. The outflow is significantly lowered during summer dry periods with gradually increases sea influence, especially in the conditions of increased exploitation for tourism. Salinities on some karst coastal springs rise over 2000 mg/l and water becomes useless for water supply. However, it must be emphasized that the first rains return the system to normal conditions and springs become completely fresh water springs. Totally different situation is on the islands, especially on small and medium ones, where due to aquifer heterogeneity mostly irregular lenses of fresh or brackish water with limited dimensions exist. The attempts of brackish water catchments combined with desalinization to provide the water supply of distant islands are in progress. The problem is renewal of reserves, because the gradual increase of salinity is expected, which significantly increases the expenses for desalinization process.

The type of the sea water intrusion into fresh water aquifers is connected mainly with geological conditions, so on the Adriatic coast in Croatia there are differences from place to place. The system genesis during Quaternary age in the whole Adriatic and Mediterranean region and the sea level changes that enabled the advance of karstification processes a lot deeper than the present sea level and finally the sea water intrusions into the boundary parts of fresh water aquifers during the sea level raising after the last ice age, should always be considered. Local intrusions are possible only on the places of limited contact, opened to sea influence on relatively narrow area. Such examples are the spring site Perilo in Bakar bay and the spring site Duboka Ljuta near Dubrovnik (figure 2). However, these cases don't represent exclusive season intrusions, because for example in Perilo the salt water is always present and the system is recharging and discharging depending on the fresh water pressure. The major part of coastal aquifers is connected to regional intrusions and dynamic contact of fresh and salt water in the deep parts of karst aquifers. The best illustration is cone raising of brackish water due to over exploitation, sometimes even dozens of kilometers distant from the shore. Increasing number of private wells, where the control of exploitation during the summer dry periods is lost, creates the problems. The example is the south part of Istrian peninsula, where besides the water supply wells more than thousand private wells have been drilled that are totally out of control. Similar situation is in the region Ravni Kotari in the central Adriatic region. Coastal region along the mountain chain Velebit has specific characteristics with numerous submarine springs, periodically very strong (figure 3) for which it could be said that they have typical channel type hydraulics explained in papers by Đurašin (1943), Pavlin (1973), Bonacci (1995), etc.

Figure 2. Duboka Ljuta - Dubrovnik (photo: R. Buljan).

Figure 3. Submarine springs along Velebit.

The system genesis is connected to changes in the sea level during the Quaternary age, however even today the coastal system is in constant dynamic changes. Several elements have the permanent influence. First, there are cyclic changes of climate conditions, and then there are the conditions and the quantity of exploitation, the changes of water balance of coastal aquifers, the global climate changes and the whole sequence of changes in local conditions that could influence the changes in coastal regions.

Cyclic changes of climate conditions with duration up to ten years are the known phenomena and they are hardly separated from the influence of global climate changes. On the Vrana lake on the Cres island they have been monitored since 1925 (figure 4). However, the interesting part is the constant trend of the lake level decrease through the measuring period without any significant changes in the immediate catchment area. The other important element is the constant increase of exploitation quantities in existing objects and the new ones, which significantly decreases the fresh water quantities for keeping the balance with the sea water. The major changes in the water balance of coastal karst aquifers emerged after the construction of hydroenergetic objects some thirty years ago, which significantly decreased the fresh water inflow during the summer dry periods, because numerous swallow holes with constant outflow in most part of the year remained dry. The new objects have not been built now, but the optimization of work on existing ones is made by towering the dams and by managing system that is adapted to production of electricity (HPP Rijeka, HPP Senj, HPP Obrovac, system of HPPon the Cetina river, system of HPP on the Neretva river, HPP Dubrovnik). It is difficult to claim that the global climate changes have provoke the major changes in exploitation of coastal aquifers, but the existing scenarios of possible effects show the sea level increase up to one meter in the next 100 years. The very thought of such conditions has to provoke the dilemma of how to carry on, because it would for sure have the negative effects on the coastal fresh water systems, and especially on the island systems. The changes in ground hydraulics could have catastrophic consequences on the fresh water exploitation in the coastal regions. Of course, there is the whole sequence of possible influences because of local changes, from the infiltration to moving of waters into other catchment areas.

Figure 4. Vrana lake on Cres.

Besides the classic confrontation with the consequences of the sea water intrusions that took place in the last thirty years, when the whole water supply systems were salinized, the users today are more and more equipped to prevent the water supply system salinization. The most commonly used measures are the measuring of CND in the springs and automatic shut off pumps if the

water exceeds the standards for drinking water. The first project on the spring site Perilo in Rijeka (Bakar bay) for control of mixture zone in the deep parts of aquifer to enable the partial shut off pumps, which enters into the sphere of optimal management of nature system, is in progress. One borehole with the depth of 150 m below sea level will be drilled and sensors for CND measurements will be placed, with the possibility of automatic shutting off the pumps in the catchment object. More and more the methods of geohydrochemical analyses and modelling are used. Special value has the modelling of microelements, which could indicate the migrations of specific elements from saturated sea water into poorly saturated fresh water medium in the conditions of completely fresh water. This method was used for investigations of Vrana lake on the Cres island, which proved the theory of open lake fresh water system towards the sea influence and in that way the gradual increase of exploitation with constant monitoring of characteristic indicators was proposed. It can be stated that the hydrogeochemical methods are in the state of constant development, but in increasing usage as the "early warning system" as well.

MANAGEMENT

The State Direction for waters and Croatian Waters, as the executive institution for the management, are responsible for the water systems management thereby including coastal systems. Croatian Waters are, in accordance with European Union Directive, divided into 4 managing units, from which two of them, Rijeka and Split, manage the coastal and island water systems. Each of those managing units has groups for usage, protection and defense against floods.

The State Direction for Waters and Croatian Waters are organized and functioning in accordance with The Law of Waters, which is the upmost one for the water systems management in the Republic of Croatia, as well as for the coastal and island water systems. The Law of Island Development has also the influence on the development of water systems, especially in the water supply organization. Along with The Law of Waters there are the whole sequence of Regulations, whereby The Regulation of Protection of Drinking Water Springs and accompanying Directions should be singled out.

The managing mechanism uses wide range of means for efficient management of coastal and island water systems. The usage of artificial recharge, which becomes more and more the important mean of preserving the coastal aquifers, could be divided in two main groups in Croatian conditions. The first are the direct catchments for artificial recharge, which is not used often. There is one example of efficient usage on the Istrian peninsula, where the waters of surface accumulation in flysch are introduced into ground for recharge of the biggest natural spring on the peninsula (Gradole) during the summer dry period. However, today this system is abandoned and the water from the accumulation is purified and directly used for the water supply. The case of increasing the spring waters after accumulation construction for hydroenergetic uses of water is far more frequent, because the usual losses of accumulation are the big contribution for karst underground. This was the way of stabilizing the main water supply springs of the city of Split (Jadro, Žrnovnica). The artificial recharge could become the mean of preserving the aquifers on some small islands (Susak). Today in the Adriatic coastal region there is still no using of waste waters for eventual creation of barriers.

The karst aquifer groundwater from natural springs and catchments is predominantly used for the water supply system in the coastal region, but for the part of the coast south of Split and the islands of Brač and Hvar, the purified water from the river Cetina is used. Similar is the situation in peak summer consumption on Istrian peninsula, where the water from artificial accumulation Botonega is purified, as well as partial use of the river Cetina for water supply of Zadar.

In the management system there are no prescribed ways for necessary decreasing of

exploitation, and the individual cases are connected to the necessary needs for each water supply system. It is known that the water supply systems maximally use cheaper electricity during the night for the exploitation and almost as the rule this is the time of maximal exploitation when almost all the salinization occur. The daily equalization of pumping of needed quantities have already reduced the problem of aquifer salinization. It should be emphasized that in Croatia, within the remediation of problem of sea intrusion into coastal aquifers, several grouted curtains were build, mainly with low effects, so very expensive technical constructions are today almost completely replaced with appropriate managing systems.

In Croatia the water is mainly used for water supply of inhabitants, tourism and remaining industry, and very little for the agriculture, because there is the specific type of predominantly rocky coast, where it is impossible to develop agriculture. The agriculture in karst regions is mostly connected to karst poljes, which are high in the catchment area and are not connected with the problem of coastal water supply, except through the aquifer protection system. Only in the south of Istria the agriculture is developed and numerous private wells are used for the irrigation, without any real control and suggestion possibility.

Because the water is used mostly for water supply of inhabitants and numerous tourists, it has to have strict standards for drinking water, which is the case with all water supply systems in Croatia. It is emphasized that the karst groundwaters in Croatia are of naturally high quality, especially during the summer dry periods, when the consumption is the highest, because the epikarst aquifer zone has the maximal protecting function. The danger comes with the first strong water wave, when the epikarst zone is washed out and the springs are weighted mostly with increased turbidity and bacteriological pollution.

The water transfer from one catchment to another is not very usual phenomenon in the water supply, because this requires significant finance, however the water transfer from the mainland springs to islands and from the island to island belongs to this group of activities. Many of the big islands are connected to the water supply from the mainland, completely or partially. The examples are the islands of Krk, Rab and Pag in the northern part of the Adriatic and the islands of Brač, Drivenik, Hvar, Korčula and Elafiti in the southern part. However, the new water supply plans are in great extent conceptually connected to distant water transfers from water resources, which are not yet used in the right extent (Gacka, Kupa). The water usage in Croatia is mostly owned by local government (cities, districts) and they have mostly inherited rights, but the works on establishing the concessions are in progress. However, the private wells are still out of control.

The biggest water problems are connected to the supply during the summer dry periods. The dry periods are especially expressed in the south part of coastal region, where sometimes there is no rain for more than 3 summer months. The whole water supply system of coastal region is directed to the organization during the summer dry periods, when the water quantities are the lowest and the consumption is several times greater than in winter. The attempts of water system management during the dry periods are mostly connected to the areas with the problems. If it is the question of the public sector, these are the optimal measures, at least in dated moments, as previously described. But in the combination with the private users this has no real value, except to emphasize the problem.

In the mainland region there is still no need for desalinization of water from coastal aquifers, however for the small distant islands this is very actual. Up to now, only one desalinization device functions on the island of Lastovo (south Adriatic) and several such devices that should use the local brackish waters on the islands are in preparations.

It should be emphasized that in the Croatian Waters, several years ago, the Department for Water Management was formed that is responsible for the forming the basis of water economy with all strategic directions for future relation with water resources within the sustainable devel-

opment of the Country. The treatment of coastal aquifers is not satisfactory comprehended by this project, although the future problems could be huge. The problem of the sea influence on the karst aquifers is treated mainly by scientists in Institute of Geology in Zagreb, whose participation in COST 621 project "Management of coastal karst aquifers" had the influence on the international level. Together with the Institute the scientists from the universities in Zagreb, Rijeka and Split and the whole sequence of small private firms that work from project to project, are active.

The monitoring in the summer dry periods is limited to several localities included in COST 621 project. These are the springs in Bakar bay, Novljanska Žrnovnica and Vrana lake on the island of Cres. In the other areas there are no real monitoring objects (deep boreholes) and for now, there are no needs because the fresh water quantity is sufficient.

The true management of coastal water systems is in the beginning, in those areas with problems, which are Istria, north Adriatic (Rijeka) and wider area of the city of Zadar. Within the management organization, according to European Union Directives, far better effects on the coastal aquifers under the sea influence could be expected.

CASE STUDIES

6.1 The Vrana lake on Cres island, Croatia

The Vrana lake on Cres island is one of the most important and interesting water phenomena within the Dinarc karst, and most probably, even within the Mediteranean region. The lake is formed in a cryptodepresion on an elongated relatively narrow island built mainly of karstified carbonate rocks of Cretaceous and Paleogene ages (figure 5). With its volume of 220 millions m^3, the lake is the only potable water resource for the very touristically developed islands Cres and Lošinj. The lake surface is about 5,5 km^2. A gradual trend decrease last 15 years was the main reason for the start of a complex interdisciplinary exploration activities to determine the genesis of the lake, hydrodynamic changes that have occurred, how to protect the lake and to estimate its potential for public water-supply use.

In general, about Vrana lake two ideas of its genesis have been launched: closed in its own catchment area or open to the deep karst underground with the influence from wide area (recharge and discharge). Hydrogeologists tried to keep both ideas open, trying to find a proper answer by means of complex exploration.

The morphology of the lake bottom with the deep sinkhole in southern part point out the idea of link with the wider area, it means the link with the genesis of the river Po delta as whole, and indicates a hydraulic connection with a deep karst underground and possible active connection with the sea water. The depression was formed in the Pliocene, when numerous lakes within the Dinaric karst were formed. During the Pleistocen, depression was in a form of karst field, what is comfirmed by the finds of fluvial sediments. In that time sea water level was some 100 m under its present elevation (Šegota, 1983) and the whole northern Adriatic region was the river Po delta. The rise of sea level after the last glacial period resulted in the rise of fresh water in the karst underground and creates the present hydrogeological situation in that region. The open doline-type depression where surface water during karst field phase used to sink before the sea-water level rise, makes possible a hydraulic connection between the lake and a deep karst underground in present situation.

Analyses of the recent lake bottom deposits indicate an origin of the deposited sediments away from the close catchment area on the island because of the content and position of the heavy mineral fraction, which was concentrated in the vicinity of deep depression.

The analyses data and hydrogeochemical reflections are results of long term monitoring and analyzing of the Vrana lake water under different seasonal conditions (figure 6; Biondić, *et al*, 1997). The lake displays an obvious thermal stratification with one entire annual water over-

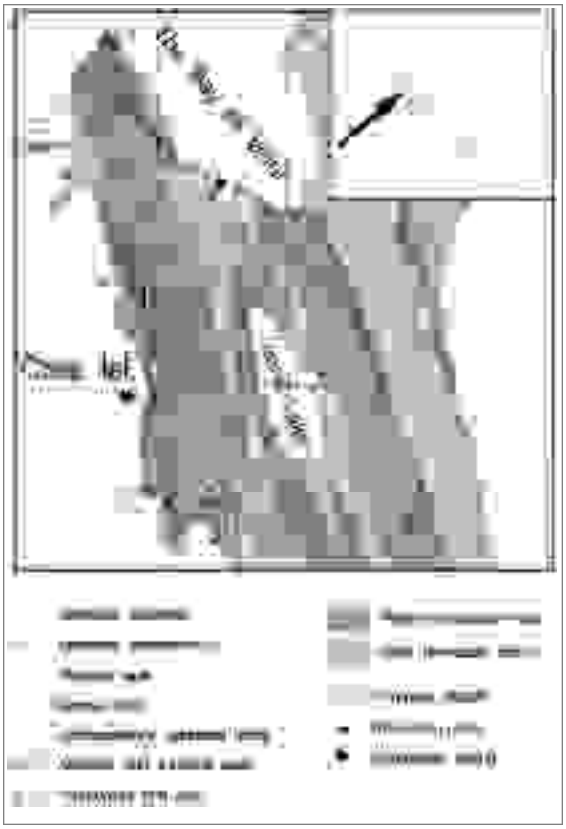

Fig. 5. Schematic hydrogeological map of the Vrana Lake.

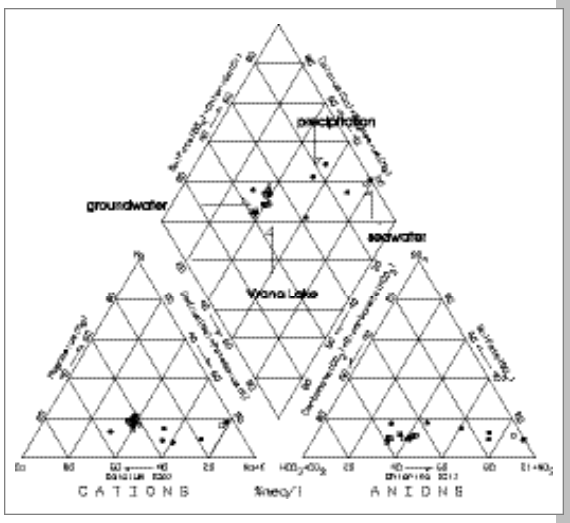

Fig. 6. Piper diagram of water from the Vrana lake catchment area

turn, which is characteristics of monomictic lakes. A small amount of decomposed organic matter, a good aeration of lake water and extremely low concentration of nutrients reflects the oligotropic feature of the lake system.

The distribution of the lake water temperature along the depth follows the annual thermal stratification regime not exceeding 8,3 to 8,5 °C at the lake bottom most of year. The isothermic state is usually stablished by the end of February, at about 7 °C. In the same time, groundwater temperature is between 12,8 and 15 °C in the boreholes at the lake sides and this corresponds to the local climate. It means that two different thermic media exist there. CND is different too. The isotope analyses express an effective mixing of the entire lake water. Hydrogeochemical modeling show the prevailing share of precipitation in the composition of lake water (70 to 75%) and the possible share of groundwater of long residence time from a deep karst underground of about 7%. The conclusion is that Vrana lake is in hydraulic balance with the other media, with its deep karst underground and the Adriatic sea, and the future increase of the exploatation rate from the lake must be continuously strictly controlled because of the possible sea water intrusion.

Coastal spring Novljanska Žrnovnica

Novljanska Žrnovnica spring area supplies the region of Novljansko-crikvenička Riviera with drinking water. The exploitation capacity is up to 230 l/s, however, the determined possibilities reach the 400 l/s without major interventions in the spring area. The site is placed in deep sea cove that opens the possibility of direct contact between fresh water system and the sea. The catchment area of the spring area is widening in a fan form towards Gorski Kotar (Lič polje) and Lika (river Gacka valley) and diversity of the inflows is determined by geohydrochemical investigations (stabile isotopes) (Biondić, *et al.*, 1999).

The development of tourism caused the increase of the need for drinking water, so, since

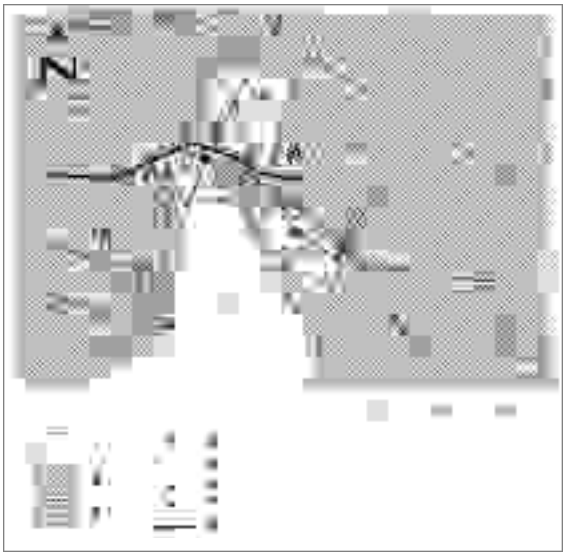

Figure. 7 Protection zones map of water-supply site Novljanska Žrnovnica.
1. IAprotection zone; 2. IB protection zone;
3. Zone of calcareous breccias; 4. Intake structure;
5. Piezometric borehole; 6. Vrulja;
7. Temporary coastal spring; 8. Grout curtain position.

the catchment at the spring area, the pumping quantity is permanently increasing and additional water catchments were made. In the mid seventies the first salinization problems begun, so the project to separate the fresh water from the sea was made (Pavlin, 1973) and the project of grouted curtain in phases had started (figures 7-8). The first phase was successful, because it was the plugging of the subsurface weathered zone between the sea and the one of the catchment solutions (the old catchment). The effects were good and it was the encouragement for further works. The part of the second phase has also been done, but without any significant results, because it was all to shallow for deep karst groundwater flows.

The problems with water quantity in the spring area again emerged in the dry summer period in 1994 and the new constructions were needed to increase the drinking water quantities. The ideas about the continuation of grouted curtain construction were stopped and the attention was directed towards the hydrogeological events

Figure 8. Position of transition zone on water-supply site Novljanska Žrnovnica.

in the deeper part of the spring zone and towards the certain modifications in water supply of the central pumping basin. In the first phase two boreholes were drilled with the depth of 110 m (PŽ-1 and PŽ-2) between pumping site and the sea (figures 7). The borehole PŽ-1 was entirely within carbonate breccias, which are, on the site of Novljanska Žrnovnica spring, of the molassic origin in reference to karstified limestones of lower Cretaceous age, which are the main aquifers in the spring area. The breccias are of a very low permeability and they build the barrier between fresh water mass and the sea. However, the borehole PŽ-2 gave entirely different results although it is only 50 m away from the borehole PŽ-1. In the first place it was drilled through permeable limestones and, what is far more interesting, at the depth of 90 m below the surface, well permeable horizon with artesian pressure was found and water burst from the borehole. Continuous measurements determined the existence of upward flow in the mixture zone of fresh and salt water (figures 8) that represents the natural barrier between fresh water and sea system (Custodio, 1985). The test pumping of the catchments in summer 1999 determined the possibility for pumping water from the pumping site with the capacity of 400 l/s without the increase of salinity in the borehole PŽ-1, but also without any changes in borehole PŽ-2, which confirmed the

stability of determined relation between fresh and salt water in the pumping site (Biondič, 2001).

Novljanska Žrnovnica spring area is a good example of successful combination of technical construction and water system management.

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