Small-scale water quality monitoring networks

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ABSTRACT

Silva, E.M., Costa, M.F., Barletta, M., 2013. Small-scale water quality monitoring networks. In: Conley, D.C., Masselink, G., Russell, P.E. and O'Hare, T.J. (eds.), *Proceedings 12th International Coastal Symposium* (Plymouth, England), *Journal of Coastal Research*, Special Issue No. 65, pp. 1218-1223, ISSN 0749-0208.

The monitoring of seawater physico-chemistry using automated buoys is well developed for large oceanic scales. Accessible and easy to handle small-scale monitoring buoys and land-based receivers are still missing in coastal water monitoring. River basins, reservoirs and estuaries are the most stressed aquatic environments as a result of their intensive use. These water bodies, and adjacent coastal waters, are priority candidates for continuous and reliable water quality monitoring. Environmental Agencies establish monitoring programs that involve water sampling and laboratorial analysis. Small-scale automated monitoring systems work with relatively low costs if simple materials and readily available technologies are used. We propose the development of a monitoring system that involves small plastic buoys/moorings with temperature and salinity probes, signal emitter/receptor devices, and Programmable Logic Controller (PLC) with wireless communication. The proposed technologies already exist, but need to be developed to work together in inhospitable environments as salt water and high temperatures. It is indicated for the continuous monitoring of shallow water bodies within coastal conservation units, municipal water reservoirs and even by environmental agencies in an upstream/downstream design to monitor water intake and effluents discharges from industries and water treatment plants. Private users may also be interested in installing the system if they are responsible for the maintenance of the water quality of coastal environments. Cheaper and efficient water quality monitoring is key to the building of meaningful time series that can be statistically treated to allow predictions of water quality changes.

ADDITIONAL INDEX WORDS: *nature conservation, aquatic monitoring, physico-chemical variables, water management, automated technologies*.

INTRODUCTION

One of the biggest challenges of Brazilian environmental agencies is to ensure the sustainability of coastal / estuarine ecosystems (Barletta *et al*., 2010). These ecosystems are of great importance for the conservation of the marine fauna and flora, while carrying a significant attraction for human occupation (urbanization) and socio-economic activities. According to the Brazilian Institute for Geography and Statistics 2010 census (IBGE: www.ibge.gov.br), 24% of the population lives in the coastal zone in Brazil, which means ~45 million people. Large industrial centers, port activities, mineral processing and pulp plants, shipyards and shrimp farms as well as some industrial sectors, such as chemicals and petrochemicals all also concentrate in this region (Filet & Jablonski, 2008). These factors, when associated, confer high susceptibility to environmental damage to these ecosystems.

In these areas, there is a gradation of environments Land → Basin → Estuary → Sea, all interconnected forming an *ecocline* (Barletta & Costa, 2009). The estuaries are the interface between the out flowing river and adjacent ocean, being an integral part of the coastal zone (Figure 1). From the classical definition of Pritchard (1967) - the estuary is a coastal body of water, semi-enclosed, which has a free connection to the sea and within which sea water is progressively diluted with fresh water from the drainage surface -, the main physical phenomenon of the estuary is the mixing between saltwater and freshwater.

Human activities require large amounts of good quality water for their deployment and continuation. The main source of this resource is usually the watershed / river basin. By using the water resources of the basin, human action decreases the flow of freshwater contributing to the estuary. This is one of the many possible symptoms of river basin / coastal syndromes (Meybeck, 2003; Newton et al., 2012). The withdrawal of water upstream in the watershed determines greater intrusion of the seawater on the continent. The more the sea enters the continent, the lower the availability of freshwater and nutrients to the coastal zone, which due to mixing with seawater becomes salty / brackish. If this process becomes continuous, permanent damage may be caused to the irrigation and specialized coastal ecosystems. Also the water supply of coastal populations may be compromised. Thus, salinity, as an essential characteristic of estuarine environments, can also be understood as an indicator in a relationship of cause and effect, which connects the upstream activities to the ecological effects of the basin on the coast (Habib *et al*., 2007). It is justifiable, therefore, among the various elements that can be used as indicators of the functioning of coastal and estuarine environments the use of salinity as its main variable. This physico-chemical variable fulfills an important role in the distribution of communities of flora and fauna (Barletta *et al*., 2005, 2008; Dantas *et al*., 2010; Barletta *et al*., 2012) and is essential for the establishment of economic activities dependent on water resources, especially where uses may be limited due to salinity (or scarcity of surface water resources, as in semi-arid regions).

DOI: 10.2112/SI65-206.1 received 07 December 2012; accepted 06 March 2013.

The need for water resources management in coastal and estuarine systems is expressed in most policies of government agencies at all levels of the public administration. Actions such as controlling the distribution of flow between consumers who pay for water use and monitoring of coastal areas are among the most discussed factors. In Brazil, the various instruments of water management are defined by the National Water Resources Plan (PNRH), which is the main legal guideline on the subject, and was established by Federal Law No. 9433 of 1997. This plan presents several management tools (Table 1), in order to maintain the quality, quantity and timing of freshwater flows.

The management tools provided in the PNRH serve as important reference for control actions of estuarine and coastal environments. Through the granting of rights to use water resources, for example, you can set the limits for each user within each basin. This can be used as a criteria for setting limits of minimum flow to be maintained in the outlet for limiting the saline intrusion, so as to preserve optimal water availability for all users and for nature conservation.

The criteria for classification of water bodies according to their predominant use, which are set by Resolution No. 357 of 2005 of the National Council for the Environment (CONAMA) is another instrument with practical application in the coastal zone. In that Resolution the environment is divided into: freshwater, brackish and saltwater, with respective subdivisions based on the predominant use. So, fundamental uses as primary contact recreation, public supply and aquatic life conservation, have more restrictive limits of the physic-chemical parameters. The monitoring of salinity aims at the maintenance of a pattern, or a particular range of salinity, which represents the dynamic nature of this variable within estuaries. This is to be monitored so as to not compromise the different and many water uses nor the ecosystems conservation needs.

In practice, it is observed that the results predicted in the national water monitoring and conservation plans are far from being achieved. A major difficulty is to monitor anthropogenic effects on these ecosystems (Loitzenbauer & Mendes, 2011). The monitoring via satellite through automated buoys is already quite common for monitoring of ocean waters, mainly due to the interest in climate research. However, this monitoring in coastal environments is still quite precarious; limited to campaigns of collecting samples for subsequent chemical analysis in specialized laboratories.

These field campaigns are undertaken by the governmental (Federal, State or Municipal) agencies and are susceptible to technical, operational, and political issues. Often the data series are interrupted due to limitations that could be easily overcome if at least some automation was in place. Besides, the sampling frequency can also be a problem. Water quality changes within hours of interferences are made. So, monthly or bimonthly monitoring might be enough to, in a long term time scale, monitor water quality and quantity for decadal trends. However, for instant interferences from accidents (or from intentional discharges) and even for seasonal and inter-annual variations these are not enough.

Society can interfere with water quality and quantity in a very short timescale, and monitoring systems must be able to detect that. On the other hand, the built of time series for medium and long term studies need to allow for the filtering / reading of data at different time intervals for a significant period of time. In this way, the acquisition of data needs to be consistent enough to allow sampling within the databank for different sample designs of different objectives.

Another paramount necessity of existing water quality monitoring systems is the extension of the sampling locations. Usually arrays are limited or set according to old criteria. To expand the sampling arrays will call for automated methods that can increase the locations without having to immediately abandon the historical ones.

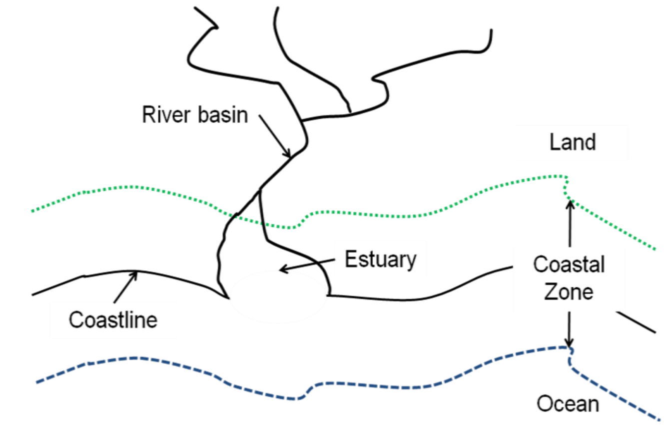

Figure 1. The coastal zone is a continuous of ecosystems that form an *ecocline*. This gradient starts at the watershed / river basin, and flows transporting freshwater, nutrients, organic matter and energy to coastal waters. Along its way it may also transport pollutants and impacts to the sea.

Table 1. Instruments of the Brazilian National Water Resources Plan from 1997.

Legal instruments of the Brazilian National Water Resources Plan
I - Water resources Plans
II - Classification of water bodies according to its main uses
III - Use permissions
IV - Charging for uses
V - Water resources information systems

This paper presents a system capable of monitoring environmental variables (e.g. salinity and temperature) by means of a compact, relatively inexpensive system, capable of communicating wireless with buoys. When installed in river channels and estuaries, provides online data, measuring the main water quality variables, forming a network of small-scale environmental conditions monitoring.

The monitoring system consists basically of a control center, using PLC (Programmable Logic Controller) with a SCADA supervisory system, using the variation in salinity as the main control variable. Sensors for measuring salinity along the river channel are used on buoys which transmit remote signals. The salinity was chosen as a conservative parameter present in the estuarine domain, which can be taken as an indicator of the structure of these ecosystems (Barletta *et al*., 2005, 2008; Habib *et al*., 2007; Dantas *et al*., 2010; Barletta *et al*., 2012).

Flow control systems for water users in estuarine zones or just upstream from estuaries, can be controlled automatically by a PLC, which can open and close valves located at great distances from the control center. The system proposed here was developed and tested in tanks in the laboratory. During the tests temperature and salinity were systematically altered to adjust the design of the system. The range of variations mimicked the values observed in estuarine systems of the Brazilian Northeast.

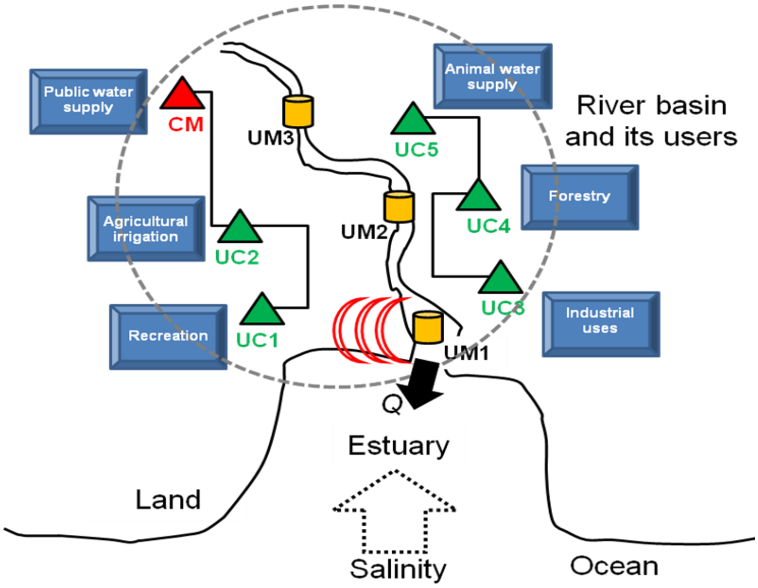

Figure 2. Monitoring network and its main elements. CM = central monitoring unit; UC = control units; UM = monitoring units - buoys; *Q* = water flowing to the estuary from the river basin.

METHODS

Experimental Set-Up

The initial steps for designing the water quality monitoring system were taken based on demands form a research group who needs to monitor salinity with in an estuarine system and temperature in order to determine fish movements and patterns of habitats use by different ontogenetic phases of key species for artisanal fisheries (Dantas *et al*., 2010; Dantas *et al*., 2012).

The first system was then conceptually conceived (Silva *et al*., in press) taking as example the Goiana River Estuary (Barletta & Costa, 2009), where the conservation of natural resources (mainly patches of Atlantic Rain Forest, mangrove forests, water, fish crustaceans and shellfish) is the basis of an Extractive Reserve (RESEX).

The many different and conflicting water uses around and within this Marine Conservation Unit derive from poor land use practices and water management, but also from the semi-arid climate across the river basin, before it reaches the humid coast.

Beyond the small river basins and estuarine environments of the Brazilian Northeast, there are potential testing scenarios at other Conservation Units that suffer from water issues as the Fernando de Noronha Archipelago, at the Equatorial Atlantic, where a Marine National Park and an Environmental Protection area share scarce land and water resources.

We proceeded with an analysis of the integrated management model proposed by Loitzenbauer and Bouillon (2011), based on taking control parameters established by PNRH for coastal and estuarine environments. In this analysis were observed which parameters had been identified as essential for integrated watershed management. From this analysis was designed an automated system for water monitoring on a small scale, so that all controls described in PNRH could indeed be implemented using the resources of the automation system.

In their model Loitzenbauer and Bulhões (2011) used the mass balance of salt applied in a one-dimensional estuary. These types of models allow to establish the physical relationship between the net inflow of freshwater and salinity (Babson, et al. 2005; Habib et al, 2007). The mass balance was applied to a hypothetical estuary. However, the results show that the variation in salinity may faithfully reflect the environmental conditions of a real estuary.

In designing the system it was also considered that users of the watershed, by withdrawing water from rivers and streams, modify the flow of freshwater to the estuary, changing the dynamics of salinity. Thus, any situation where the inflow decreases due to the increase in water demand along the basin, or decreased precipitation, will cause a change in the dynamics of salinity, e.g. the mixing zone.

Another important aspect considered in the development of the system were the salinity limits established by the WHO (World Health Organization). For public supply, the threshold is set by 1‰. For irrigation, salinity tolerance varies for each crop. Rice, for example, can tolerate up to 2.5 ‰, but not the soil. Due to the continuous evaporation of water, the concentration of salts in the soil increases gradually. The plants grown in saline soil suffers from drought and the toxic effect of excess ions (Marcondes & Garcia, 2009). The watering of animals can not be performed with brackish water (salinity above 0.5 ‰) and also industrial use may be limited due to salinity.

The monitoring system and automated control can be deployed to create a network of small-scale environmental monitoring in a coastal / estuarine environment. By means of electronic resources, monitoring and remote control, it is possible to install a central monitoring (CM), equipped with a PLC and supervision software, installed distant from coastal environments, at an urban center, for example. The CM receives the data on-line, the monitoring units (UM), which are buoys equipped with sensors for salinity and installed along the axis of the basin, and control units (UC) consisting of control valves flow, servo-actuated remotely installed at points of consumers intake (Figure 2).

Functions of the monitoring and control units

- Central Monitoring Unit (CM): installed in the administrative center with the PLC and SCADA supervision software (Figure 2). The PLC has communication capability, at various and long distance, via the industrial networks, and can receive data, online measurements, performed by the systems measuring buoys (UM1, UM2, ... UMn).
- Buoys: communicate with the mainland via a wireless network (Wireless), with a range of up to 500m away from the point of signal reception. On the mainland are installed modules receiving wireless signals, and these transmit data for the CM. The buoys are deployed on the axis of the river or estuary channel.
- Modules receiving signals: can communicate among them and with the PLC CM via the cable network, like Ethernet, or any other industrial network available. Thus, the Internet can be used as means of communication. In the case of Internet use, the distance between the points of signal generation and reception becomes unlimited.
- Monitoring Unit (UM): Installed at the point of capture of water in the distribution system. These buoys have the function of measuring the salinity at the point of capture (with reference to salinity 0.5 ‰). The measurement is done via the salinity sensors that provide analog electrical voltage or current proportional to changes in salinity. These signals are transmitted to the mainland via wireless.
- Monitoring Units (UM1, UM2, ... UMn): Installed at fixed distances upstream and downstream from the point of water capture. Value of salinity measured by these buoys can identify at which distance is the water of reference salinity (0.5 ‰) from the point of capture. That is, it is possible to monitor how much the salt wedge is advancing or retreating in the river / estuary.
- Units and Flow Control (UC1, UC2, ... UCn): Installed at points of large consumers. These are flow control valves servo-actuated remotely. Through them, the CM regulates the flow to be delivered to each consumer, functioning as a smart meter.

The flowchart on Figure 3 shows an example of a simplified logic for controlling the water withdraw from the basin. The value of 10% reduction of flow, for 24 hours, when salinity S reaches above the reference value (0.5 ‰) at the point of uptake was assigned randomly. But with the historical behavior of the dynamics of salinity in the estuary, it is possible to arrive at optimal values for the tuning process. This logic tends to prevent the reduction of the final flow at the entrance of the estuary. If salinity exceeds the reference value at the point of capture, the salt wedge moves toward the mainland.

Figure 4 shows the physical parts of the monitoring central (CM), detailing the posts reserved for various types of communication available. Figure 5 shows in detail the final format designed for the system's monitoring and control. The red arrows point to the devices for distance communication (wireless network antennas).

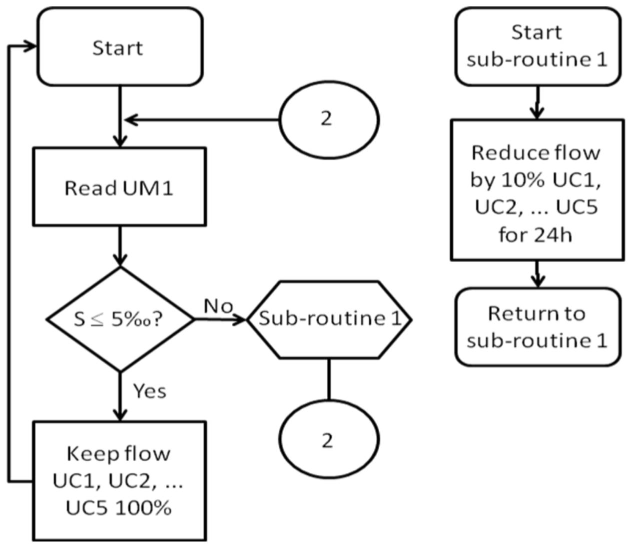

Figure 3. Flowchart of the simplified logic used in the control of the small-scale water monitoring system.

PRELIMINARY RESULTS

PLC

Through the PLC it is possible to perform online measurements of salinity at the test tank, far 300 m from the central station, with a processing time of 270µs. It was possible to make measurements and set reading intervals of hours, minutes and seconds. It was also possible to control temperature and salinity in the test tank, simulating actual conditions previously observed in an estuarine environment (Barletta & Costa, 2009) through the PID function. The programming software allowed programming in Ladder Diagram (LD), a simple language of low difficulty level. Besides it allows online editing of the algorithm, and the program can be changed during operation. It was also possible to simulate various conditions of temperature and salinity in the test tank without the PLC.

Communication system, local and remote (wireless) process monitoring

The system of communication and supervision software allowed the plotting graphs of network operations, enabled the generation of historical operating conditions of the test tank and real-time visualization of the variation in salinity and temperature via computer with both local and remote access modes.

Through the supervisory software SCADA, full engineering version, it was possible to capture data for plots that allow the temporal analysis of the behavior of the variables.

It was possible to concentrate the reception of signals of two temperature sensors and two salinity sensors, simulating the measuring buoys via the communication interface. This interface sends the data to the PLC via Wireless using the DeviceNet protocol.

It was possible to mount all the devices required to operate the system in compact suitcases, mechanically compatible and compatible, forming an appropriate set of gear that communicates via Wireless. The signal receiving module station has 16 digital inputs, 16digital outputs, analog 4 entries and 4 analog outputs, which was enough to make measurements of all the desired variables and control the temperature and flow of salt water / fresh water to control the salinity in the test tank.

Sensors / Signal Transmitters / Controller

The conductivity sensors used have specific technical characteristics that permitted the measurement of the variable in the test tank with water containing salinity close to that of seawater (35‰). The sensor has a conductivity measuring device that shows the signal measuring the conductivity and temperature on and LCD display, and also provides the parameterization of the same through keys on the front of the machine. The device also provides the analog signal into a standard compatible with the Devicenet communication system, which allowed the comparison of the signal reported by the supervisory system in the central station, and the actual value shown on the display device in the test tank. Two temperature sensors type PT100, each accompanied by a temperature controller with digital display for sampling, allowed sending the analog signal in a standard compatible with the Devicenet communication system and also the comparison with the values read from the display.

CONCLUDING REMARKS

The interfacing of mechanical, electrical, electronic elements, between all parts of the system, including the electronic control devices, allowed signal acquisition conversion, and connectivity (wired and wireless). It is a device that can serve as a research area in itself; research instrument for ecological research; and appliance for routine water monitoring and control by environmental control agencies. It is contained in two suitcases for all hardware and cables, so can transport and moved manually by the researcher or technician. All parts can be assembled physically or electrically for use without dependence on any type of tool. It is a compact and portable for easy handling.

The system will provide environmental agencies responsible for water monitoring aiming at either societal needs supply or nature conservation a new and faster tool. If properly set and operated, the system provides on line, real time data to a technical team who can then make timely decisions on water quality changes and water supply to each user.

In terms of water quality monitoring for research purposes, this system will bring an important advance since researchers will be able to control data acquisition within a large estuarine / coastal area. Also, the synoptic, continuous and spatio-temporal distribution of the data facilitates the statistical treatment and ecological interpretation of phenomena that are influencing living resources and their possibilities of use by traditional populations.

For all potential users of this water quality monitoring system the cost benefit analysis might prove to be positive for the deployment of such system. If costs with personnel, traveling, equipments, and laboratory consumables are taken into consideration, the initial implementation of the system may well pay itself within a few months of establishing its full operational conditions.

The widespread preoccupation with vandalism needs, however, to be negotiated among all the benefiting stakeholders. The system is meant to be left operating for as long as the batteries allow and sensors remain free from biofouling.

ACKNOWLEDGEMENTS

To PETROBRAS and CNPq for supporting the research through the award of a postdoctoral scholarship (Grant No. 500814/2012-0); Department of Oceanography at the Federal University of Pernambuco, through LEGECE - Laboratory of Ecology and Management of Estuarine and Coastal Ecosystems, for the support of its researchers; IFPE - Federal Institute of Science and Technology of Pernambuco, Campus Caruaru, for yielding the area for the test tank and the Mechatronics Laboratory equipment for the system's development.

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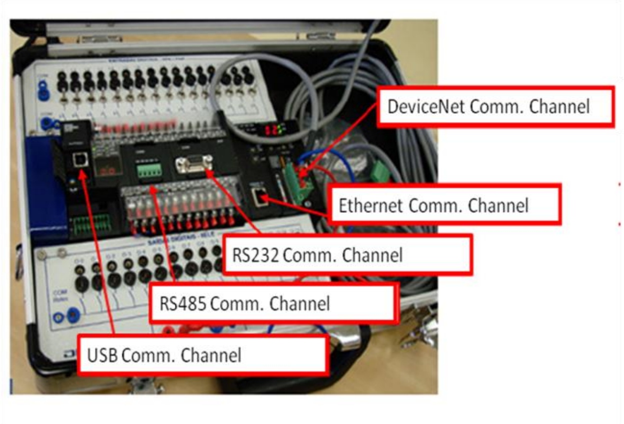
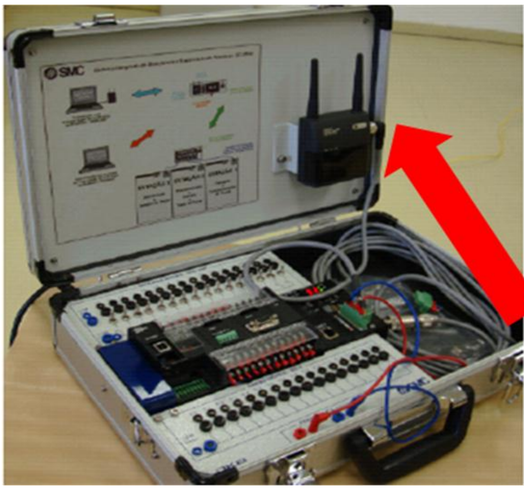
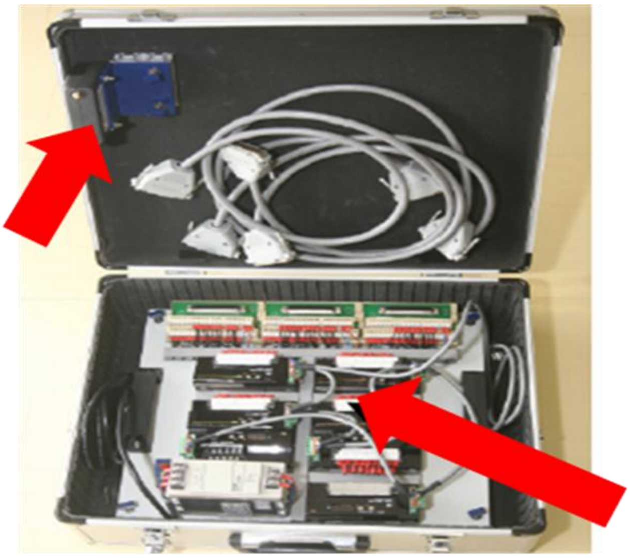


Figure 4. Portable system in a suitcase containing the PLC and means of communication with external elements. This is the main part of the monitoring system (CM).



(a)



(b)

Figure 5. Final setup of the small-scale monitoring system proposed: (a) suitcase of the monitoring units (UM); (b) suitcase of the control unit (CU). Red arrows indicate devices for distance communication (wireless network antennas).

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