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Low-Cost Alternative for the Measurement of Water Levels in Surface Water Streams

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Abstract: Flood risk management and water resources planning involve a deep knowledge of surface streams so that mitigation strategies and climate change adaptations can be implemented. Commercially, there is a wide range of technologies for the measurement of hydroclimatic variables; however, many of these technologies may not be affordable for institutions with limited budgets. This paper has two main objectives: 1) present the design of an ultrasound-based water level measurement system, and 2) propose a methodological alternative for the development of instruments, according to the needs of institutions conducting monitoring of surface waterbodies. To that end, the proposed methodology is based on selection processes defined according to the specific needs of each waterbody. The prototype was tested in real-world scale, with the potential to obtain accurate measurements. Lastly, we present the design of the ultrasound-based water level measurement instrument, which can be built at a low cost. Low-cost instruments can potentially contribute to the sustainable instrumental autonomy of environmental entities and help define measurement and data transmission standards based on the specific requirements of the monitoring.

Keywords: Measurement level gauging station, Level water monitoring, Ultrasonic sensor, Data transmission.

1. Introduction

Historical river flow records represent crucial information to assess changes in the hydrology of watersheds [1]. Land use changes, and the combined effects of climatic variability and climate change introduce alterations in the behavior of floods and the water availability in watersheds [2]. Therefore, the instrumentation of hydroclimatic variables is essential in the modelling hydrologic processes, flood prediction and alerts, engineering design, and water resource management [3-5]. Since flow records can be based on water level measurements of the monitored streamflow, it is possible to include measurements of environmental variables in addition to the water level [6].

However, water level data are usually limited or restricted [7]. Since these data are necessary to construct and extrapolate rating curves [8-9], measuring water levels requires the implementation of stations with measurement instruments, which in some cases must be low-cost solutions because of the limited resources.

Water level and flow data are obtained directly from hydrometric stations, located in rivers or waterbodies [10], whose hydrologic importance is given by the management priorities defined for the surrounding watershed. Therefore, depending on the monitoring objectives, data transmission may be required, which could strongly impact the monitoring costs and be a defining factor in the funding or sizing of a real-time monitoring network.

Also, monitoring institutions normally select technologies for the measurement of water levels according to the specific needs of the site and the available budget [11]. In consequence, the size of a hydrometric network is restricted by costs including instrument purchase, real-time data transmission, equipment maintenance and repair, and processing of the recorded data [12]. Institutions with limited resources may find challenges to install, operate and maintain dense hydrometric networks, which may result in insufficient stations and data required to model accurately hydrologic processes or describe hydrologic variations [13]. Developing low-cost measurement instruments is therefore a clear advantage in the generation of enough good quality data in the monitored sites. When linked with data transmission, water resource and risk management processes can be carried out more effectively [14].

This paper proposes a methodology for the development of ultrasound-based devices for the measurement of water levels, and data transmission via GPRS, as a technological alternative for the monitoring of flows. This technology can potentially be adopted by institutions with limited resources to obtain hydroclimatic data that can be used in the description of the behavior of the flows in the watersheds, hydrological design, water resources planning [15-16], management of flood risk [17] and protection of people's lives and assets [18]. Experimental validation was carried out in four stations of the same river located in the Colombian Andes, South America.

2. Materials and Methods

Objectives and variables should be defined when implementing a flow monitoring network as some important additional variables may exist, i.e., water quality-related. These monitoring variables are defined for a control section through a selection process of appropriate technologies for site-specific conditions.

In this study, we implemented an analytical hierarchy process AHP [19], which has been used extensively in the assessment of floods and water resources [20-23]. The selection process of each of the elements comprising the water level measurement prototype involved the evaluation of a matrix with three possible ratings. A rating of 1 corresponds to the lowest satisfaction, while a rating 3 corresponds to the highest satisfaction for a measurement characteristic, i.e., water level.

Real-world scale tests were conducted in four stations located along a 17-km reach of Combeima River, near Ibagué, Colombia [2] (Fig. 1).

Fig. 1. Location of water level (LG) and precipitation gauges (PG) in the watershed and with respect to the city of Ibagué [11].

2.1. System Architecture

The application requires signal acquisition, processing, recording and data transmission, which necessarily involves several main components on the hardware integration, each one with different possibilities and variants. First, the system needs a central processing unit CPU to manage the activities, so a microcontroller is a crucial component of the system hardware. Recording and transmitting imply the use of both a storage element and a communication device; additionally, records must be saved along with time stamps, so a digital time-clock is also an essential component. Finally, a power source for the system, e.g., a battery, is vital since most of the measurement sites are in remote places; the selected power source will determine other features such as work time, size and weight.

Fig. 2 shows the block diagram for the main elements of the system and the relations between them. Blue and red elements represent internal electronics description and power components, respectively. Power is managed efficiently by using power-conditioning electronics to adapt voltages and currents. Moreover, splitting the real-time clock consumption from the power source reduces the risk of a time deconfiguration.

General hardware is based on a microcontroller, which acquires the signal from the sensor level. In addition, it must contain the following stages: Processing, which calculates the actual value of the water level according to the census value; Data transmission, using a wireless or wired transmission module; Storage, which saves the measurement values to an external micro-SD memory; Clock, which acquires the date and time using an integrated real time clock RTC to keep the system updated; Configuration User Interface, which shows the acquired data on an

LCD display or shows possible system warnings with blinking light indicators, I/O ports and push buttons, which allow the manual configuration of system parameters when computers or USB communication devices are not available. Green and yellow elements represent the external components of the process, like the development access via USB port and the communication with a remote user via GPRS [24].

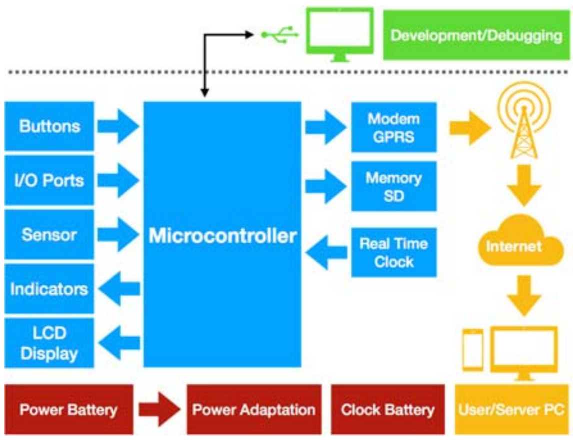

Fig. 2. Block diagram description for the main system elements.

River water level data must be acquired every five minutes with a level sensor and once the output signal is filtered, both must be saved to a micro-SD memory and sent every day to an internet server via the GPRS module. The power consumption must be optimized from electronical design for low energy consumption that results in long working time.

2.2. Design and Implementation

A matrix selection process was developed for the choice of components from the criteria and design considerations. These selection methods have been applied successfully in the field of water resources [25-26, 19, 27]. The first step in this stage was to define the sensor features; water level measurements have different methods and transductor possibilities, each with its own parameters depending on the application. For this selection matrix, we considered the main level measurements technologies, which have been used in similar [28-9]. Table 1 presents the selection matrix for six different types of sensors and twelve selection criteria based on the considerations outlined in the previous section, with a rating scale from 0 to 3, where 0 is a no satisfactory grade and 3 is a totally satisfactory grade. For each case, the quantification of the satisfaction indicator was chosen based on datasheet information.

Based on the results listed in Table 1, the ultrasonic technology was selected, even though it is not the cheapest option but a low-cost solution that fulfills the operation requirements. The choice of level sensors by ultrasound obeys to their non-invasive method, which does not compromise the reliability of measurements, and avoids and replaces mechanical blocks with great performance, sensitivity, resolution, precision and efficiency. These sensors provide output signals that are perfectly matched to the voltages and working modes in the microcontrollers, which makes it possible to record measurements on a digital system. Once the type of sensor is defined, it is necessary to choose the specific sensor from the multiple options available on the market. Table 2 illustrates the selection for the ultrasonic reference among five possibilities and ten criteria, in the same way as the measurement technology selection.

Table 1. Selection matrix for the level sensor. Type of sensors: M: Mechanic, P: Pressure, B: Bubble, R: Radioactive, C: Capacitive and U: Ultrasonic.

Selection Criteria	M	P	B	R	C	U
Implementation costs	3	1	2	1	1	2
Measurement resolution	2	3	2	2	1	3
Measurement accuracy	1	3	2	2	2	3
Measurement range	3	1	1	2	2	3
Robust operation	2	2	2	1	2	2
Easy installation	3	1	1	3	1	3
Easy transportation	3	3	3	3	1	3
Easy operation	3	3	3	1	3	3
Easy production	3	1	1	2	1	3
Availability on the market	2	2	3	1	2	2
Advantages in hardware	1	1	1	3	1	3
Output signals	1	2	2	3	2	3
TOTAL	**27**	**23**	**23**	**24**	**19**	**33**

Table 2. Selection matrix for the ultrasonic level sensor. U1: LV-MaxSonarEZ, U2: XL- MaxSonar- EZ, U3: XL- MaxSonar AE, U4: HRXL- MaxSonar- WRL and U5: SRF05.

Selection Criteria	U1	U2	U3	U4	U5
Automatic calibration	0	3	3	3	0
Temperature compensation	0	0	0	3	0
Sensor resolution	1	1	2	3	2
Sensor bandwidth	2	3	3	3	2
Minimum detection report	2	2	2	1	2
Measurement range	3	1	1	3	1
Sensor size	3	3	3	3	1
Diameter of the measuring beam at maximum distance	3	3	3	1	3
Energy consumption	3	1	1	2	1
Implementation costs	2	2	3	1	2
TOTAL	**19**	**19**	**21**	**23**	**14**

HRXL-MaxSonar®-WRL/WRLT™Ref. MB7366 from MaxBotix® was selected as the best option among the low-cost ultrasonic sensors for level measurements in surface water streams [30]. The next step was defining the microcontroller, among some microchip® family devices, given that these references have great benefits and sufficient resources to cover the needs described at a low cost [31] In addition to the microcontroller, external minor hardware components must be added to establish the clock frequency, master reset function, and circuit programming to allow the developer program the microcontroller via USB without removing the device from the system.

From the features listed in Table 3, the selected microcontroller PIC 18F4620 is the solution that best suits the requirements of the level meter system.

Table 3. Selection matrix for the microcontroller. U1: 16F84, U2: 16F877A, U3: 18F2550, U4: 18F4523 and U5: 18F4620.

Selection Criteria	U1	U2	U3	U4	U5
Communication interfaces	0	3	3	3	3
Ports availability	1	3	2	3	3
Clock frequency	2	2	3	2	3
Memory capacity	1	2	3	2	3
Energy consumption	3	2	2	2	2
Temperature operation	3	3	3	3	3
Time resources	1	3	3	3	3
Interruption options	1	2	3	3	3
ADC resolution	1	2	3	3	3
Implementation cost	3	3	2	1	2
TOTAL	**16**	**25**	**27**	**25**	**28**

The package selected was the surface mount version because of its characteristics of size, price and energy consumption. Continuing with the selection process, Table 4 presents the available low-cost devices to communicate the system with the Internet. The data transmission infrastructure was selected based on the system requirements, where one of the factors considered was the working environment, which is usually a remote, inhospitable place, without physical connection to some type of external communication. For this reason, different forms of wireless connections for data transmission were analyzed, and the alternative that was more in agreement with the project was chosen.

The power supply of the system is based on the use of rechargeable batteries, since the equipment will not always be in places with continuous power supply. Also, it results in a totally portable system, ideal for implementation in remote and inhospitable places. The selection of rechargeable battery type was based on the characteristics of Table 5.

According to the characteristics mentioned in Table 5, LiPo batteries become the best option to power the entire project. Due to its high current density and small volume, a small prototype with considerable autonomy can be developed.

Table 4. Selection matrix for the communication device. d1: SM51100B, d2: Sagem HiLo, d3: SIM340Dz, d4: Wismo 228 and d5: SL6087.

Selection Criteria	d1	d2	d3	d4	d5
Quad Band	3	3	3	3	3
EDGE	0	0	0	0	3
GPS functions	2	2	2	3	3
TCP, FTP, UDP, SMTP, POP3	2	2	3	3	3
Voltage level operation	3	3	3	3	3
Current consumption	2	3	2	3	3
GPIO resources	2	2	2	3	3
Interruption options	1	2	3	3	3
SIM target functions	0	0	0	0	3
Operation temperature	2	2	2	2	3
Implementation cost	3	3	3	2	1
TOTAL	**20**	**22**	**23**	**25**	**31**

Table 5. Selection matrix for the power battery type. b1: Pb, b2: NiCd, b3: NiMH, b4: LiPo.

Selection Criteria	b1	b2	b3	b4
Energy density	2	0	1	3
Volume / Weight	0	1	1	3
Discharging level	2	1	2	3
Internal resistance	1	1	2	3
Memory effect	1	2	3	3
Charging time	3	2	3	2
Special charger	3	3	2	1
Special care (Danger)	3	3	3	1
Implementation cost	3	3	2	1
TOTAL	**18**	**16**	**19**	**20**

2.2.1. Electronics

Once the main components of the system have been chosen, a simulation of the electronic system was carried out with Isis Proteus®. Here, the additional hardware was defined and the first control algorithms were tested along with MPlab® software. Then the general parameters were determined and the communication between the electronic devices was tested with laboratory experiments. Fig. 3 describes the main parts of the schematic diagram performed by the simulation for the electronics. The signal from the sensor is acquired on the microcontroller in both analog signal form and pulse width modulation PWM, so that the user can choose the acquisition method and the input port (Fig. 3(a)).

After the level signal from the sensor was quantified (10 bit ADC and sampled Fs=[0.833-3.3] mHz) a digital first order filter was implemented by software to remove high frequency noise, since the main data are located on the low frequencies. A low pass filter with cutout frequency "Fc" is represented with the transfer function [27]:

$$H_{(s)} = \frac{y_{(s)}}{x_{(s)}} = \frac{\omega_c}{1 + {}^{s}/_{\omega_c}}, \quad (1)$$

where $\omega_c = 2.\pi.Fc$; $y_{(s)}$ is the filtered signal and $x_{(s)}$ is the input signal. A digital implementation of equation is represented by a differences Equation (1) after the discretization process.

$$y_{[k]} = b_o x_{[k]} + b_1 x_{[k-1]} - a_1 y_{[k-1]}\,, \quad (2)$$

where $b = [b_0, b_1, b_2 \ldots b_n]$, $a = [a_0, a_1, a_2 \ldots a_n]$ are the filter coefficients [18], "k" is the sample and "n" is the filter order. The coefficients were calculated for a butterworth low pass filter using MATLAB with sample time Ts=300 seconds and Fc=10 μHz.

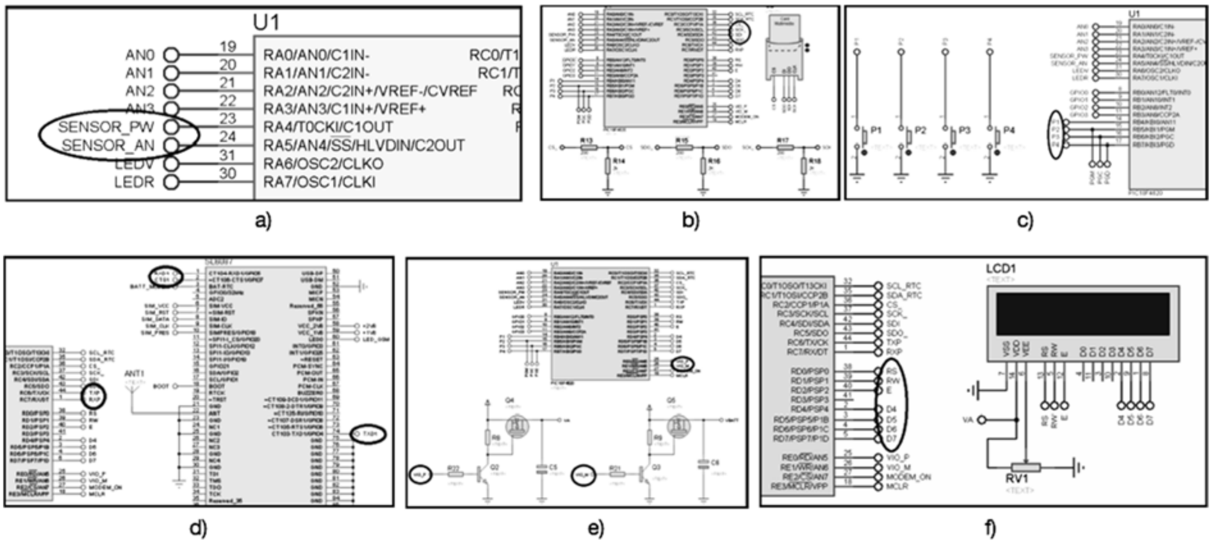

Fig. 3. A simplified circuit diagram showing the main keys elements of the electronic system: a) sensor connection for data acquisition, b) Electrical connections for data recording on SD memory, c) Electrical connections for user buttons, d) Electrical connections with communication device, e) Electrical connections for power switching control and f) Electrical connections with LCD user display.

After filtering the ultrasonic sensor signal, the date and time of the measurement were obtained by means of the RTC DS1338Z-33 by I2C communication [32]. This communication is done through software and does not use the dedicated pins of the micro because it shares the pins of the SPI and I2C communication [33]. The recording circuit requires some PULL-UP resistors of 1k Ohms connected to VCC and an external crystal to generate its own operating frequency, together with its backup battery. The filtered data are sent to the server on each sample time; however, the data can be lost by communication and connection problems, so data are saved in an internal memory with the date and hour obtained from RTC. The microcontroller records the data on a SD memory by an I2C communication on flat text file, which is reset by manual operation every three months.

The dedicated pins of the internal SPI module of the microcontroller were used for communication. The microSD memories cannot be powered with a voltage greater than 3.6 V and require a minimum voltage of 2.7 V. Therefore, a single voltage divider was used so that the upper voltage limit is restricted when the batteries are 100 % charged. The signals that need to have the voltage divider are CS, SDO, SCK (SPI protocol [34]) since they are inputs of the microSD memory (Fig. 3(b)). The buttons allow interaction with the user, to enter the various menus of the system. All messages transmitted by the control module are also displayed on the LCD screen. The buttons are connected in port B, because they have PULL-UP resistors that are enabled by program, to limit hardware components (Fig. 3 (c) and (f)).

The control the GSM / GPRS [35] uses a simplex network topology [36] and is programmed by using the AT or Hayes commands. All commands in this protocol begin with AT and end with the character <CR> (ASCII 13). The response received in the microcontroller by the modem is the following: <CR> <LF> (answer) <CR> <LF>. The communication of the microcontroller to the modem is done through the TTL-RS232 protocol, requiring hardware flow control (RTS and CTS). This flow control is needed when the baud rates are high so data are not lost during transmission. For this prototype, the work bit rate is 9600 baud, lower than the 115200 baud configured by default in the modem (see Fig. 3 (d)).

The proposed system must be optimized from electronical design for low energy consumption and to obtain a greater autonomy of the batteries. The microcontroller manages the energy supplied to the different modules of the system. The control is achieved through two MOSFET FDT434P transistors; the first powers the LCD modules, ultrasonic sensor, microSD memory, and RTC, while the second powers the cellular modem. In consequence, the devices are powered only when they are strictly requested by the microcontroller (Fig. 3(e)) to reduce current consumption [37]. An energy consumption test was performed for a work cycle of four steps: Reading, filtering and recording the data on internal memory; power commutation for communication device and sending the data to the server; and low consumption mode until the next sample time. Fig. 4 shows the current consumptions at 5 volts DC and the times for each step in a sample time. However, work time could be extended by sending consolidated data once a day according to [38].

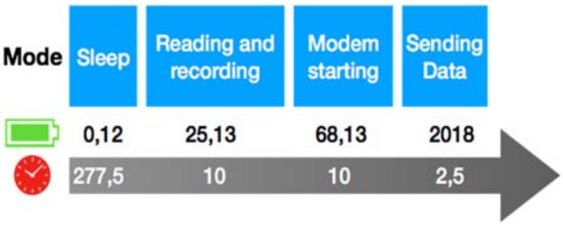

Fig. 4. Energy consumption cycle, time in seconds and battery current consumption in milliamperes.

Finally, from the test and electronic schematic, a printed circuit board PCB was designed in Proteus ARES software and the final electronic prototype was constructed (Fig. 5).

The implementation must ensure an appropriate distance over the level to be measured and a fixed and robust location with respect to the measuring point. Fig. 6 illustrates the installation modes considered and used in the implementation of the stations.

For the field installation of the stations, rating curves were calibrated by measuring flow rates and levels [39], using the methods of area-velocity and saline tracer. Programming of the devices considered the rating curves, so that for a given water level it was possible to estimate the flow in the control section.

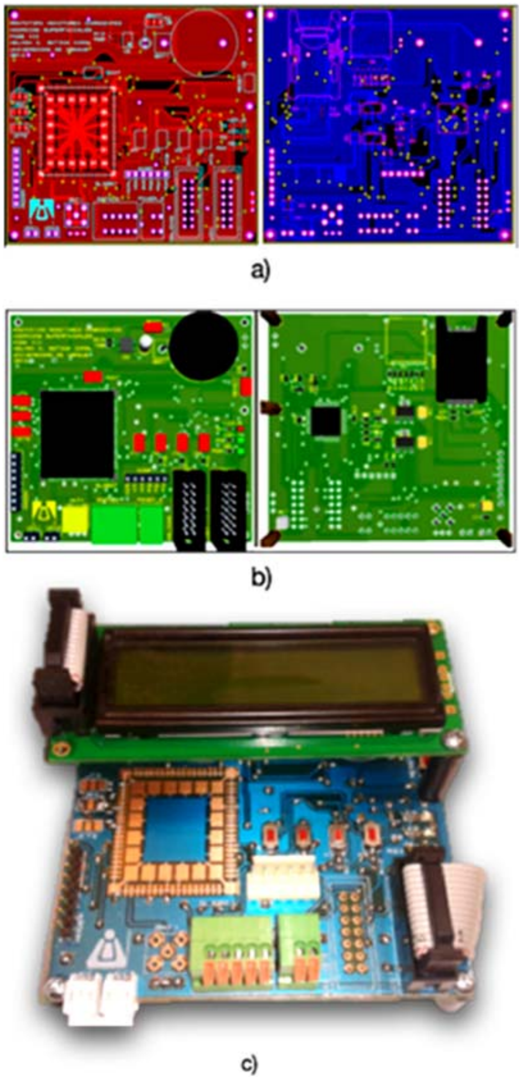

Fig. 5. Electronic system description: a) PCB design, b) 3d visualization, c) Implemented final prototype.

3. Results and Discussion

Fig. 7 presents an example of a signal obtained remotely from sensors via GPRS, and the equivalent filtered data in a period of three months with a sample time of 300 seconds. Precipitation reports in the study area at the beginning of 2014 indicate that occasional precipitation occurred, and a dry period between February and mid-March with constant precipitation in April, which implies a correlation with the obtained data.

The Pearson correlation between rainfall and flow obtained with the rating curve was 0.98 for Las Perlas Creek, 0.97 for Combeima River and 0.90 for La Plata Creek. These results indicate a high correlation between precipitation and the water level measured with the developed device in each of the streamflow measurements of this study.

The best measurement quality was obtained in slow-flowing streams, since problems with the return of the ultrasound wave were found due to the turbulence in fast-flowing streams.

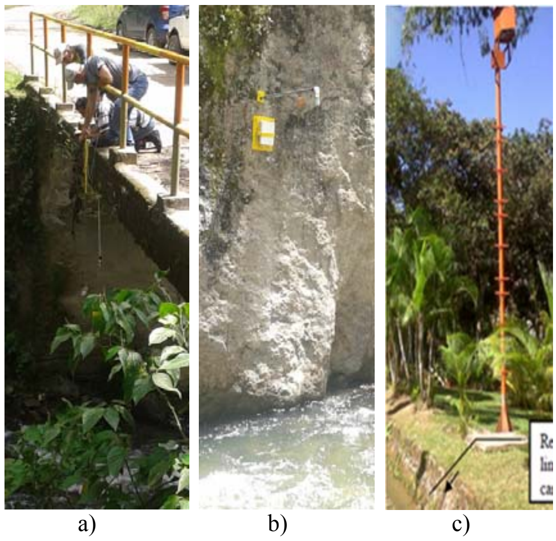

Fig. 6. Installation modes: a) Installation of the device under the structure of a bridge, b) Fixed to a slope, c) Water depletion [11].

4. Conclusions

A monitoring system for levels in surface water streams is proposed in this paper, and its effectiveness is tested via long time experimental data. These systems have low power consumption, low cost (around 35 % of the cost of commercially-available stations) and are a convenient way to monitor river water levels in real-time. Moreover, the system can be migrated to indoor living monitoring, greenhouse monitoring, climate monitoring and forest monitoring.

The ultrasonic sensor used has better noise figure in slow-flowing waters, with turbulence increasing the measurement noise.

The appropriation of technologies by institutions responsible for the monitoring and management of water resources facilitates an efficient response when solving errors in measurements or data transmission. Also, it reduces the costs of acquisition, installation, and operation. In addition, it is possible to reduce equipment replacement times, resulting in reduced gaps in the time series of flow records.

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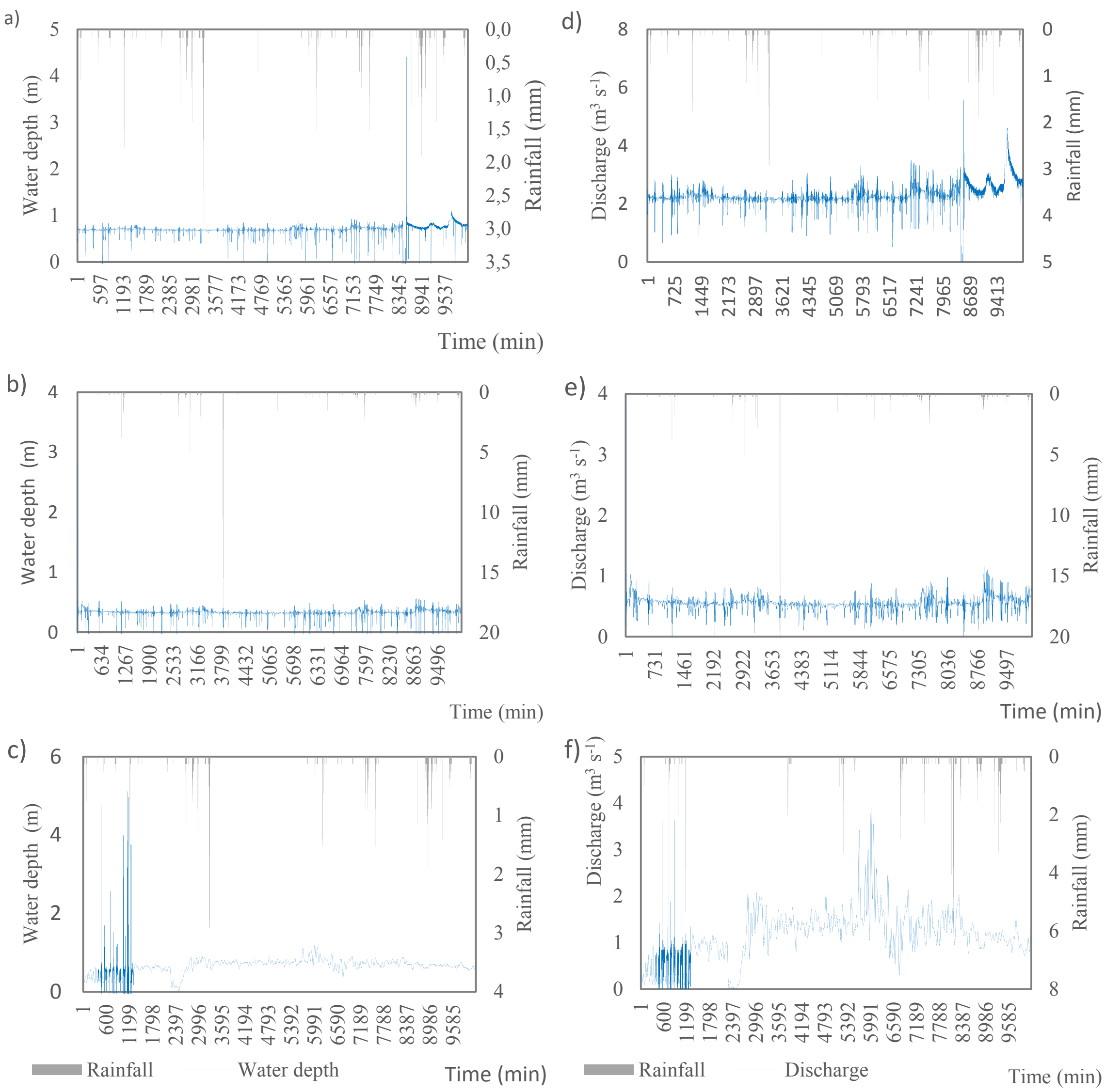

Fig. 7. Example of water level data measured in 2014. Correlation between rain and overland flow: a) Combeima River water depth, b) Las Perlas Creek water depth, c) La Plata Creek water depth, d) Combeima River discharge, e) Las Perlas Creek discharge, f) La Plata Creek discharge [11].

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