Development of an Adaptive Rainwater-Harvesting System for Intelligent Selective Redistribution

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***Abstract*—This paper presents an adaptive *rainwater-harvesting* (RWH) system based on a rainwater-collecting unit that (1) ascertains baseline water-quality in its collected rainwater via Ph- and turbidity sensors, and (2) redistributes it to designated toilet-tanks and/or irrigation points. Each unit is integrated with an XBee S2B antenna to enable cost-effective and energy-efficient mesh capabilities for inter-unit communication when two or more units conform the system. Moreover, each unit is also an *Internet-of-Things* (IoT) device that transmits water-tank levels and sensor-data to a local supervising microcontroller (MCU) via *Open Sound Control* (OSC). This MCU is, in turn, capable of communication with a cloud-based data plotting / storing and remote-control platform—viz., Adafruit IO—via *Message Queueing Telemetry Transport* (MQTT). The interface with Adafruit IO enables a remote administrator (a) to monitor water-tank levels and sensor readings, and (b) to execute manual overrides in the system—for example, any or all of the units may be shut-down remotely. When only one unit conforms the system, its water-tank services the toilet-tanks and/or irrigation points connected to the unit. When two or more units conform the system, their water-tank outputs are physically linked, enabling any unit to contribute to the servicing of a variety of connected toilet-tanks and/or irrigation points. In both single or multi-unit configurations, water redistribution is impartial to any end-point at initialization, yet over time the system identifies which end-point(s) require(s) water with a higher frequency and selectively prioritizes servicing to it/them to guarantee prompt refill / supply. The present work is part of ongoing developments of features and services that attempt to imbue the built-environment with intelligence via *Information and Communication Technologies* (ICTs).**

***Keywords*—Internet-of-Things, Cyber-Physical Systems, MQTT, Adaptive Architecture, Intelligent Built-Environment.**

I. Introduction

Rainwater-harvesting (RWH) systems can play an important role in providing limited alternatives to sources dependent on conventional water treatment to meet present water requirements [1]. Their versatile character enables them to be implemented in a variety of application domains including: cleaning services [2], farming and agriculture [3, 4], and—to a limited extent—healthcare [5], etc. Incidentally, although most of its uses are non-potable, some users have explored their potable potential—for example, 25% of respondents in a survey conducted on members of the *American Rainwater Catchment Systems Association* reported to use rainwater for potable purposes [6].

The present paper situates RWH systems within the intelligent built-environment discourse. The detailed RWH system is presented as an open-ended and highly scalable system for the intelligent selective redistribution of collected-water (with tolerable Ph and turbidity levels) to toilet-tanks and/or limited irrigation points based on the frequency of requirement. The system is a *Cyber-Physical System* (CPS) [7] composed of one or more rainwater-collecting units designed as *Internet-of-Things* (IoT) devices capable of communicating with one another (when consisting of two or more units) and with a cloud service (viz., Adafruit IO [8]) via a supervising *Microcontroller Unit* (MCU). Data pertaining to water-tank levels as well as sensor-readings from each module is streamed to said cloud service, which also enables override interventions in the system's local operation (see Section II and Section III for technical details). The physical / mechanical resolution of the system is developed to a *Technology Readiness Level* (TRL) [9] of 4, while its informational / computational resolution—which is based on established *Information and Communication Technologies* (ICTs)—is developed to a TRL of 9. The RWH system represents a highly technological (in terms of ICTs) type of RWH systems, one capable of open-ended scalability; and of employing ICTs to enhance its serviceability and performance over time. In the context of the authors' ongoing developments of features and services that attempt to imbue the built-environment with intelligence, the system is construed as a potential sub-system within a larger highly heterogeneous ecosystem sustained by a self-healing and meshed *Wireless Sensor and Actuator Network* (WSAN), whose underlying System Architecture is presented and detailed elsewhere by the authors [10].

The development of the system is presented in five sections. In Section II, the *Concept* and its corresponding *Approach* are described in detail. In Section III, the *Methodology* and *Implementation* of two instances of a fully functional prototype are described. In Section IV, sample *Results* are presented and discussed. Finally, in Section 0, a *Conclusion* including a discussion of limitations as well as future development and application is provided.

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II. Concept

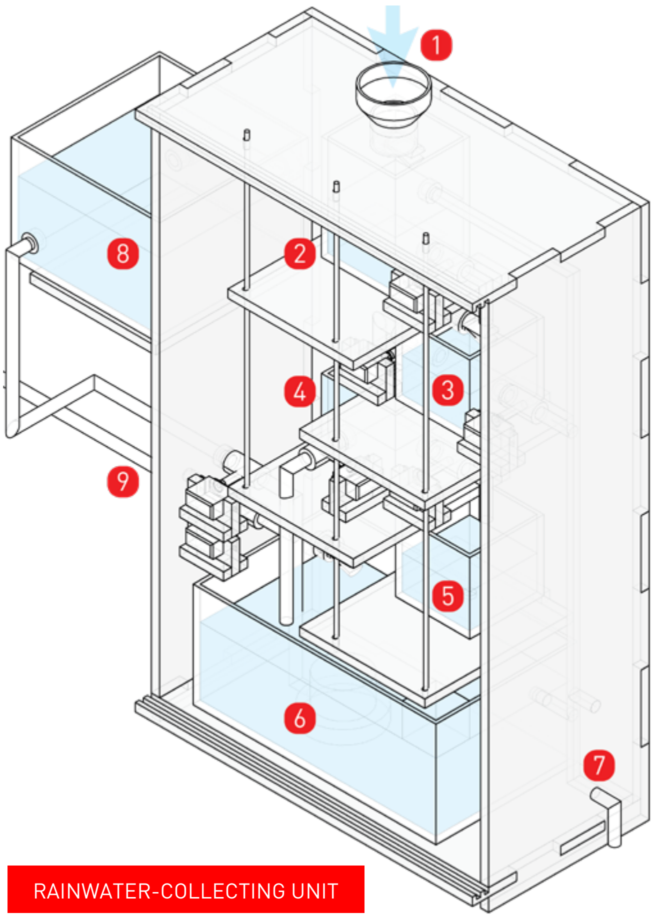

Figure 1. System layers: (1) collection of rainwater; (2) 1st storage tank; (3) 2nd storage tank, measurement of Ph-levels; (4) 3rd storage tank, measurement of turbidity—if levels exceed 5 NTUs, the water is released to the main, otherwise it is passed through (5) a ceramic filter in the 4th tank (if between 3.5 – 5 NTUs), or sent directly to the (6) 5th and general collection tank (if <3.5 NTUs); (7) Outlet for all releases to the main water system; (8) 6th water tank, representing a toilet-tank; (9) if the toilet-tank is full, contained water in the 5th tank is released for irrigation.

The operation of each rainwater-collecting unit in the RWH system consists of nine layers (see Figure 1 and Figure 4). In the first layer, rainwater is collected via a funnel—equipped with a meshed filter to exclude visible particulates—installed directly below designated water-draining points (typically on the roof and/or on regions of walls immediately below the roof). Alternatively, and instead of the funnel, a drain-pipe connected to a protected water-catchment point may be directly connected to the unit. The water is collected into the storage tank of the second layer, which holds collected water until a minimum of one liter is obtained. In the third layer, the Ph-levels of the water are gauged, and if it is either hazardously acidic or basic, it is immediately released to the main water system. If, however, the Ph-levels are within 6 to 8.5, the water is passed to the storage tank of the next layer. In the fourth layer, the water's turbidity levels are gauged. If the water exceeds 5 *Nephelometric Turbidity Units* (NTUs), it is released to the main water system.

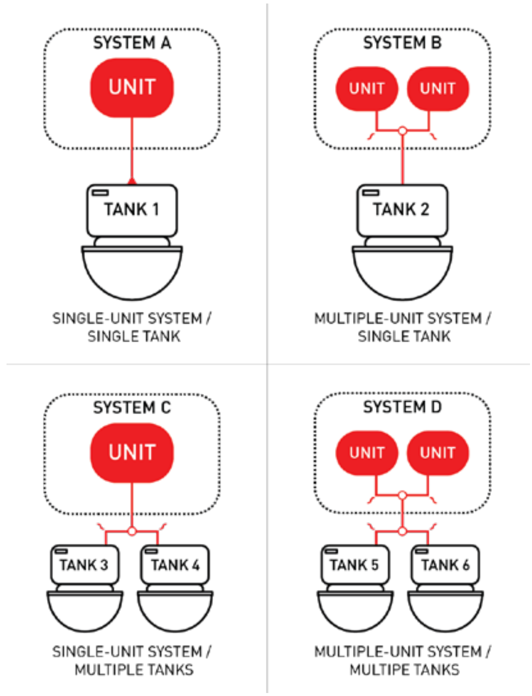

Figure 2. Deployment Configurations. Top-Left: a single-unit system servicing a single tan. Top-Right: a multiple-unit system servicing a single tank. Bottom-Left: a single-unit system servicing multiple tanks. Bottom-Right: a multiple-unit system servicing multiple tanks. N.B.: '~' symbol indicates location of servovalve & water-flow sensor.

If, however, it is between 3.5 to 5 NTUs, the water is passed to the fifth layer for filtering. And if turbidity levels are below 3.5 NTUs, it is passed directly to the sixth layer, bypassing the need for filtering. All collected water with non-hazardous Ph- and turbidity-levels is stored in the tank of the sixth layer, which has a maximum capacity of ten liters. A water-sensor is attached near the rim of the water tank, which informs all previous tanks to withhold passing water until levels are reduced. The tank in the sixth layer itself cannot overflow, as an outlet connected to the main water system is installed near the rim. The seventh layer is where all the connections to the main water system meet into a single outlet. The eighth layer represents the toilet-tank, although it may also represent a reserve tank additional to the toilet-tank depending on the requirements of the user. Finally, the ninth layer represents the irrigation outlet, which is optionally engaged—likewise by means of servovalves—as a release mechanism when the tanks are at full capacity.

When the system is conformed by a single unit or multiple units servicing only one toilet-tank (see Figure 2, *Top-Left* and *Top-Right*), no reconfiguration of parameters is required in the unit's program or electronics. In the case of a single-unit system servicing multiple toilet-tanks (see Figure 2, *Bottom-Left*), the outlet pipe of the ten-liter tank furcates to correspond to and connect with each toilet-tank. Immediately past the point of furcation, corresponding servovalves and water-flow sensors are attached at the root of each diverging pipe. Minor modifications to the unit's program and addition of the servomotors to the MCU must be undertaken to meet the physical configuration demands. N.B.: In the present TRL-4 physical design, each unit is capable of servicing a maximum of two ultra-low-flow toilet-tanks (~six liters per flush) in situations of simultaneous flush, provided that the storage tanks across all operation layers are full. In Figure 2, *Bottom-Left*, the output of the ten-liter tank of system C's unit bifurcates to connect to toilet-tanks 3 and 4, with a servovalves and water-flow sensor integrated at each furcation. The flushing of either toilet-tanks 3 or 4 (or both) is detected by the water-flow sensor—i.e., as the toilet-tank empties, a pressure differential draws water from the system. If toilet-tank 3 is to be prioritized due to a detected higher frequency of usage, then the servovalve controlling the flow to toilet-tank 4 is restricted (see Section 0 for the reasoning behind such selective restriction). In the case of a multi-unit system servicing multiple toilet-tanks (see Figure 2, *Bottom-Right*), the ten-liter tank outlets of all units are linked into one outlet in order to instantiate a single source of collected rainwater. As in the case of a single-unit system servicing multiple toilet-tanks, the single-source outlet furcates to correspond to and connect with each toilet tank, where a servovalve and a water-flow sensor is attached at the root of each furcation. This setup also requires minor reconfigurations to the program and electronics of each unit. The same selective restriction by servovalves at the furcation of pipes enables a selective prioritization of service to a given toilet-tank.

As the RWH system is a CPS, in parallel to the above-mentioned activities, a corresponding set of activities taking place informationally / computationally are also taking place in tandem correspondence. As stated briefly in the *Introduction*, all sensed data and water-tank levels are transmitted by each unit to a supervising MCU. Moreover, the states of all servovalves and water-flow sensors (in cases of a single-unit system or a multiple-unit system servicing multiple toilet-tanks) is also communicated to said MCU. This MCU first verifies if malfunctions have occurred—i.e., if the unit or units have deviated from expected states and ranges. If it has, the MCU shuts the system down automatically. Regardless of malfunction, all received sensor and actuator data across the system (i.e., across all units in the network) are streamed to a cloud-based data plotting / storing and remote-control platform, viz., Adafruit IO via *Message Queueing Telemetry Transport* (MQTT) (see Figure 5 for sample streamed-data plots). A remote administrator—say, the owner or care-taker of the building—is able to view the states of all sensors and actuators across all units in the deployed system. He/she can also intervene with a manual override via MQTT to the local system. For example, suppose tank 3 in Figure 2, *Bottom-Left* is being selectively prioritized by the local system due to a detected high frequency of use. In such a case, the remote administrator could override this to prioritize tank 4 or to reset all priority weighs to instantiate an initial state of impartial distribution. Furthermore, the setup enables the remote administrator to shut-down all units across a system during a dry period. The ability to interact with the system remotely is one of the salient characteristics of the present system, and one that may be expanded to include non-human control. For example, instead of a remote administrator deciding that a period is dry, this may be objectively determined via Dark Sky [11], which works with Adafruit IO.

III. Implementation

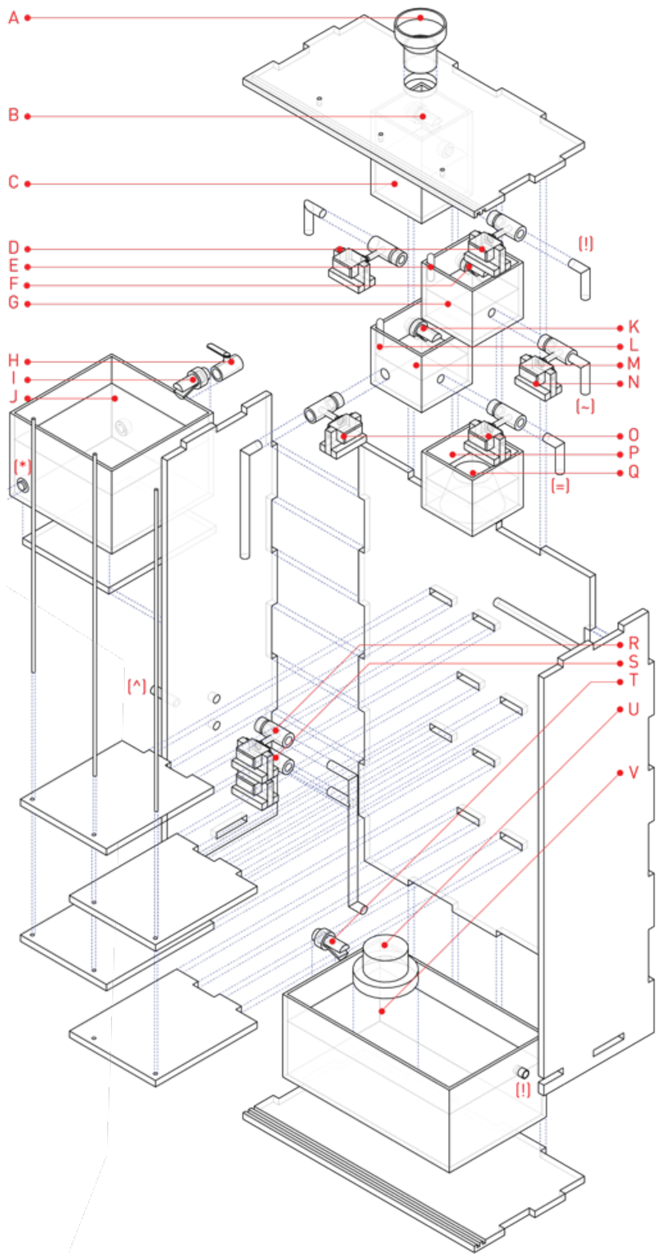

Figure 3. System breakdown: (A) rainwater downpipe; (B) water-level switch; (C) 1st container, 1L capacity; (D) servovalve; (E) Ph sensor; (F) water-level switch; (G) 2nd container, 0.5L; (H) manual valve, representing flush-lever / -handle; (I) water-level switch, representing toilet tank-float; (J) 6th container, 5L, representing toilet-tank; (K) water-level switch; (L) turbidity sensor; (M) 3rd container, 0.5L; (N) servovalve (O) servovalve; (P) 4th container, 0.5L; (Q) ceramic filter; (R) servovalve; (S) servovalve; (T) water-level switch; (U) water-pump; (V) 5th container, 10L; water-sensor installed to measure levels; (!) overflow-outlet; (~) outlet to the main, for harmful Ph levels; (=) outlet to the main, for high turbidity levels; (*) intake to toilet water-tank; (^) outlet to irrigation (when toilet water-tank is full).

The physical / electronic part of the system is built with three ¼" tie-rods, six acrylic water-tight tanks, a ceramic water-filter (particular to dissolved solids), a 2" funnel, threaded hoses, and triplex wood (see Figure 3 and Figure 4).

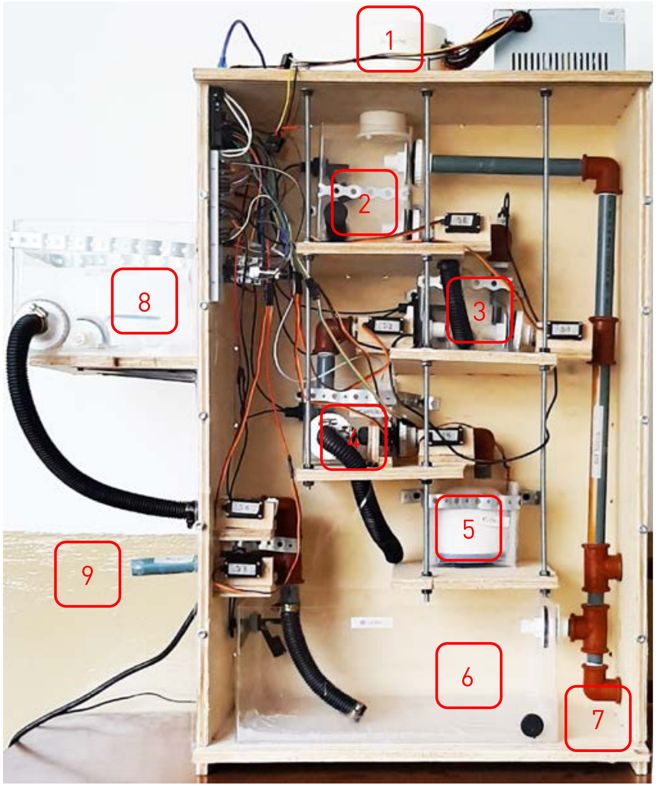

Figure 4. System layers, photograph of one of two implemented prototypes. N.B.: Numbered items correspond to those detailed in Figure 1.

With respect to the ICTs: each unit is integrated with an XBee S2B antenna via a shield on its MCU to enable cost-effective and energy-efficient mesh capabilities for inter-unit communication when two or more units conform the system. Each unit is designed as an IoT device that transmits water-tank levels, Ph- and turbidity sensor-data, servovalve states, and water-flow sensor-data to a local supervising MCU built with a WiPy 3.0 board on a PySense shield. This local transmission takes place via OSC. The supervising MCU, in turn, streams gathered data every minute to Adafruit IO via MQTT. The communication between the supervising MCU and Adafruit IO is programmed with Adafruit IO's API in MicroPython.

Once one prototype was successfully built and tested, a second instance is built in order to simulate a two-unit system servicing two toilet-tanks (see Figure 2, *Bottom-Right*). To undertake functionality tests, the toilet tanks are simulated virtually to gauge the behavior of the prototypes in a simpler manner. All other systems are implemented fully and functionally using commercial and/or open-source TRL-9 ICTs. Nevertheless, since the TRL of a system is determined by the TRL of the least-mature sub-system or component, the present overall implementation is at TRL 4.

IV. Results

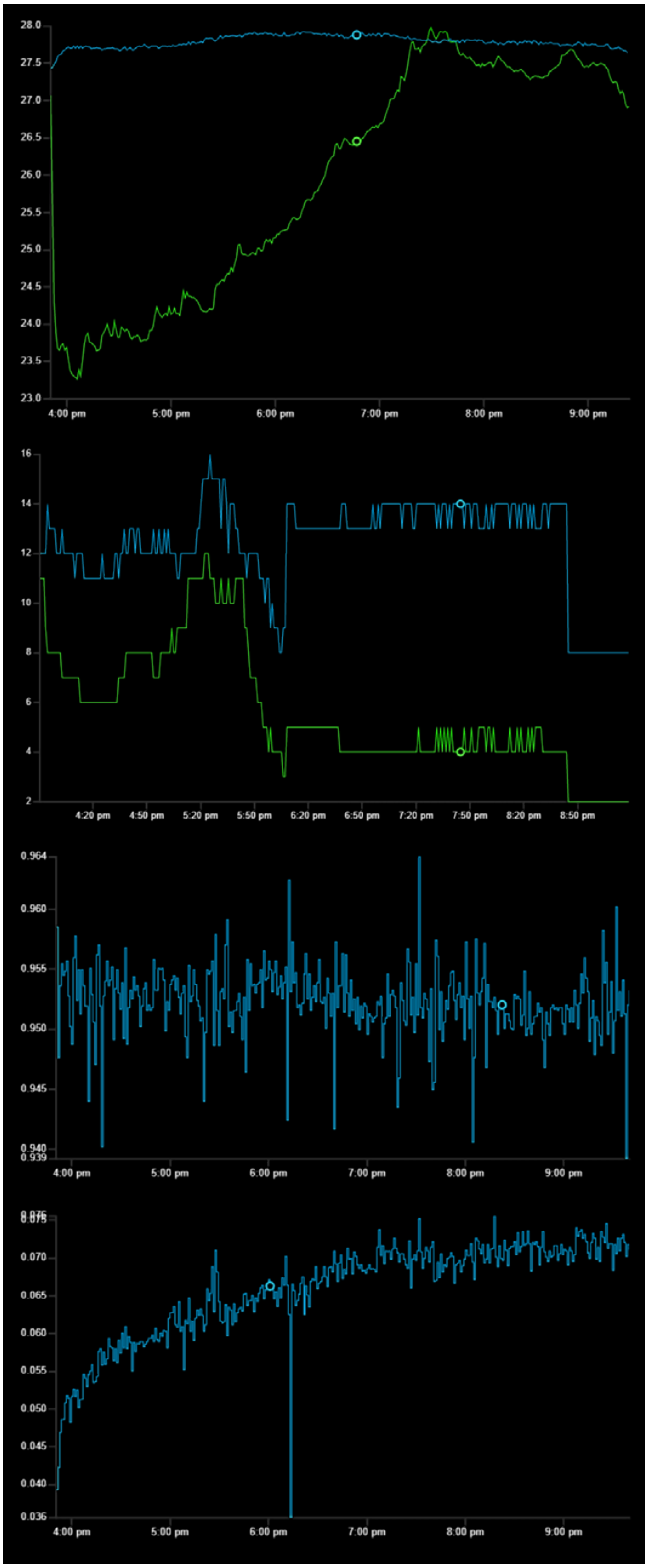

Figure 5. Plotting by Adafruit IO, one-minute intervals. Top-Down: Toilet-tank levels A&B; Prioritizing tank A (blue); Ph- and turbidity-levels, unit A.

The prototypes were tested in several configurations and scenarios continuously for a period of 24 hours. During this time, the local supervising MCU disconnected from Adafruit IO twice due to an exceeding of streaming frequency rates for free-accounts. This was resolved by slowing the streaming to once every minute. During this period, negligible leakage was observed in a number of servovalves, which was resolved via software by reconfiguring rotation values. Also, the ceramic filter's rate of filtration was measured to be unacceptably slow for a higher TRL development, and hence a new filter was purchased. Nevertheless, the physical / electronic part of the system performed as expected. As may be gathered by the first and top image of Figure 5, the transmission of sensor-data from rainwater-collecting units A and B to the supervising MCU, and then from this latter to Adafruit IO was successful. Also, as shown in the second image of the same Figure, selective prioritization of toilet-tank A's levels (plotted in blue) was verified in a simulated synchronized flushing of both tanks, as toilet-tank A refills more rapidly and to a higher level than toilet-tank B. Finally, the two bottom images in Figure 5 show successful tracking of Ph- and turbidity sensor-values transmitted from unit A.

V. Conclusions

This paper presented an adaptive RWH system based on a rainwater-collecting unit capable of ascertaining baseline water-quality in its collected rainwater via Ph- and turbidity sensors, and of redistribution it to designated toilet-tanks and/or irrigation points. As an RWH system, it represents one of the first IoT and CPS solutions that imbues remote control capabilities via cloud services. Its performance was reliable and its implementation cost-effective. The authors view the system as an appropriate solution for low-income housing communities, where water scarcity renders waste of potable water untenable.

A word on the reasoning behind selective prioritization of distribution of collected rain-water: it may be argued that such a selective prioritization of toilet-tank refills is trivial, as regardless of which toilet-tank is prioritized, others will still be filled by the main water system. While this consideration is true, the objective with selective prioritization is not an argument for independence from the main water system, but one for a reduction of consumption from said system. That is to say, if toilet-tank A is actually used five times more frequently than toilet-tank B, then allocating as much collected rainwater to toilet-tank A does indeed represent a reduction of consumption from the main water system. Of course, if the difference in usage is negligible, then the selective prioritizing of refills inherits is almost trivial. However, when viewed in the long run, even if one toilet-tank is flushed one time more than others, savings will accumulate over time. Economic considerations aside, selective prioritization reduces waste.

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