HIGH-RESOLUTION AUTOMATIC WATER QUALITY MONITORING SYSTEMS APPLIED TO CATCHMENT AND RESERVOIR MONITORING

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Introduction

Automatic recording instruments provide the ideal means of recording the responses of rivers, lakes and reservoirs to short-term changes in the weather. As part of the project 'Using Automatic Monitoring and Dynamic Modelling for the Active Management of Lakes and Reservoirs' (LIFE98 ENV/UK/000607), a family of three automatic monitoring stations were designed by engineers at the Centre for Ecology and Hydrology in Windermere to monitor such responses. In this article, we describe this instrument network in some detail and present case studies that illustrate the value of high resolution automatic monitoring in both catchment and reservoir applications.

The instrument network

The schematic diagram in Fig. 1 shows the key features of the instrument network designed for this project. In functional terms, the network includes three principal sub-systems: the remote station (typically located at the laboratory), used to retrieve the acquired data; the communication systems that relay data from monitoring stations using either a combination of uhf radio telemetry and a telephone landline or a direct link via a GSM (cellphone) data modem; and the monitoring stations themselves. Three different types of monitoring station were designed for use in the project:

1. Automatic River Monitoring Stations (ARMS) for monitoring the physico-chemical properties of rivers;
2. a basic Automatic Water Quality Monitoring Station (AWQMS) for monitoring the weather and the near-surface properties of lakes/reservoirs;

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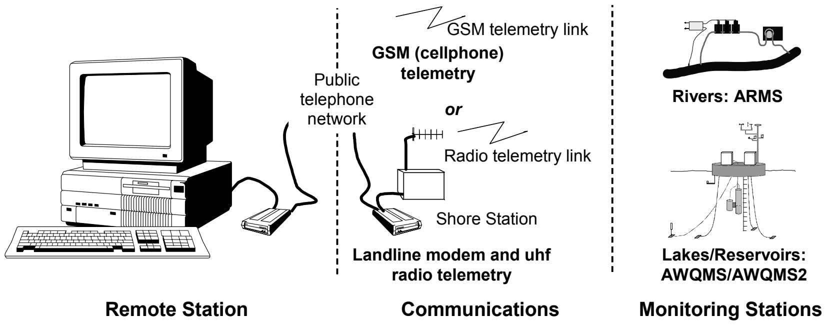


FIG. 1. The principal features of the instrument network deployed in this project.

3. a more advanced 'profiling' version of the Automatic Water Quality Monitoring Station (AWQMS2) for monitoring the weather and the vertical variations in the physico-chemical properties of thermally stratified lakes/reservoirs.

The remote station

The remote station consists of a PC running Windows-hosted software and connected via a modem to the telephone network, which allows a remote operator to establish a connection to the selected monitoring station and then to:

1. retrieve data recorded by the monitoring station;
2. alter the configuration of the monitoring station (e.g. the recording interval for a specified variable);
3. view the data acquired by the monitoring station in real time;
4. retrieve diagnostic information to check the performance of the monitoring station;
5. establish a 'direct connection' to sub-assemblies within the station (for detailed diagnostics/configuration);
6. update the software used to control the monitoring station (e.g. to add new features).

Communications

Two principal methods can be used to transfer data from the monitoring stations. Where the monitoring station is installed at a location with GSM (cellphone) coverage, the data can be downloaded via a GSM data modem and the telephone network. In areas without GSM coverage, a low power uhf radio link is used to relay data to a conveniently located 'shore station' connected to the telephone network. At the shore station, a microcontroller linked to a uhf radio data transceiver and telephone modem handles all communications with the monitoring station or stations. The shore station can be contacted by telephone at any time to establish communications with the monitoring station. This telemetry configuration provides low operating costs, but ‘line-of-sight’ conditions between the shore station and the monitoring station antennae are required for reliable operation at the maximum range (ca. 10 km). The data transfer rate from the monitoring station to the shore station is limited to 9600 baud (about 1000 characters per second) but this gives satisfactory download times even when high-resolution, minute-by-minute data are to be downloaded.

Unusually in this project, one of the Automatic River Monitoring Stations was accessed via a land-line telephone connection as the location of the site meant that radio or GSM communication would have been difficult to achieve and telephone land-lines passed near to the site. In general, where the local topography prohibits the use of either GSM or point-to-point low power uhf radio telemetry, more sophisticated methods are possible (for example, using uhf radio relay stations or satellite communications). More recently, where internet connections are available, it has become possible to use internet protocol communications to connect from a remote station to a shore station rather than using the telephone network. There are two key advantages to using an internet link for this purpose: it is free to use (i.e. no call charges are incurred) and it is ‘always on’ (i.e. there are no significant delays in establishing the internet connection, whereas a dial-up data call via the telephone network takes around 30 seconds to establish the connection).

Monitoring stations

All three monitoring stations share core technologies. They are all:

- based on a Campbell Scientific data logger (Models CR23X and CR10X);
- contactable remotely via a telemetry system;
- ruggedly constructed using military quality connectors and environmentally sealed enclosures;
- capable of high temporal resolution (minute-by-minute) and high accuracy measurements;
- low maintenance designs requiring visits at typically two- to four-week intervals.

The lake/reservoir systems also feature:

- additional circuitry to enable remote monitoring of instrument performance;
- remote diagnosis capabilities;
- circuitry to allow direct communication to selected sub-systems;
- remote control of electrical power to the individual sub-systems;
- expansion options to accommodate additional sensors.

Table 1. Specification of the sensors fitted to the Automatic River Monitoring Stations in the Burrishoole catchment, Ireland.

Parameter	**Sensor Type**	**Range**
Water temperature	Stainless-steel sheathed platinum resistance sensor (PRT)	-5°C to +40°C
Water level	Semiconductor strain gauge	As required
Dissolved oxygen concentration	Polarographic cell (Clark cell)	0 to 500 % saturation
pH	Combination electrode	2 to 14 pH units
Conductivity	3–electrode (graphite) cell	0 to 2000 $\mu S\ cm^{-1}$
Suspended sediment	Nephelometer	Dependent on sediment composition

The Automatic River Monitoring Station (ARMS)

The Automatic River Monitoring Station (ARMS) builds on experience gained from the design of a stand-alone profiling system (Rouen 1989). Table 1 lists the environmental parameters recorded by the station. All the sensors used can be obtained commercially and were selected to provide the best combination of accuracy and proven reliability. The sensor used to measure the concentration of suspended sediment is relatively new, but tests showed that it could detect suspensions of peat silt at concentrations below 0.02 $g\ l^{-1}$.

Automatic River Monitoring Stations were deployed in the Burrishoole catchment in Ireland. Three different installation methods were devised to ensure their safe operation:

1. the installation of an array of sensors in a protective cage secured to the river bed;
2. the installation of an array of sensors in a flow-through chamber situated on the bank of the river, where a flow of water was maintained by a self-acting hydraulic ram pump;
3. the installation of an array of sensors in a flow-through chamber situated on the bank of the river, where a steady flow of water was maintained by a self-priming electric pump.

Option 1 is the simplest option and was used on the Glenamong River where there was little risk of flood damage (Fig. 2). This system is mechanically quite robust but can only be used on rivers where there are no

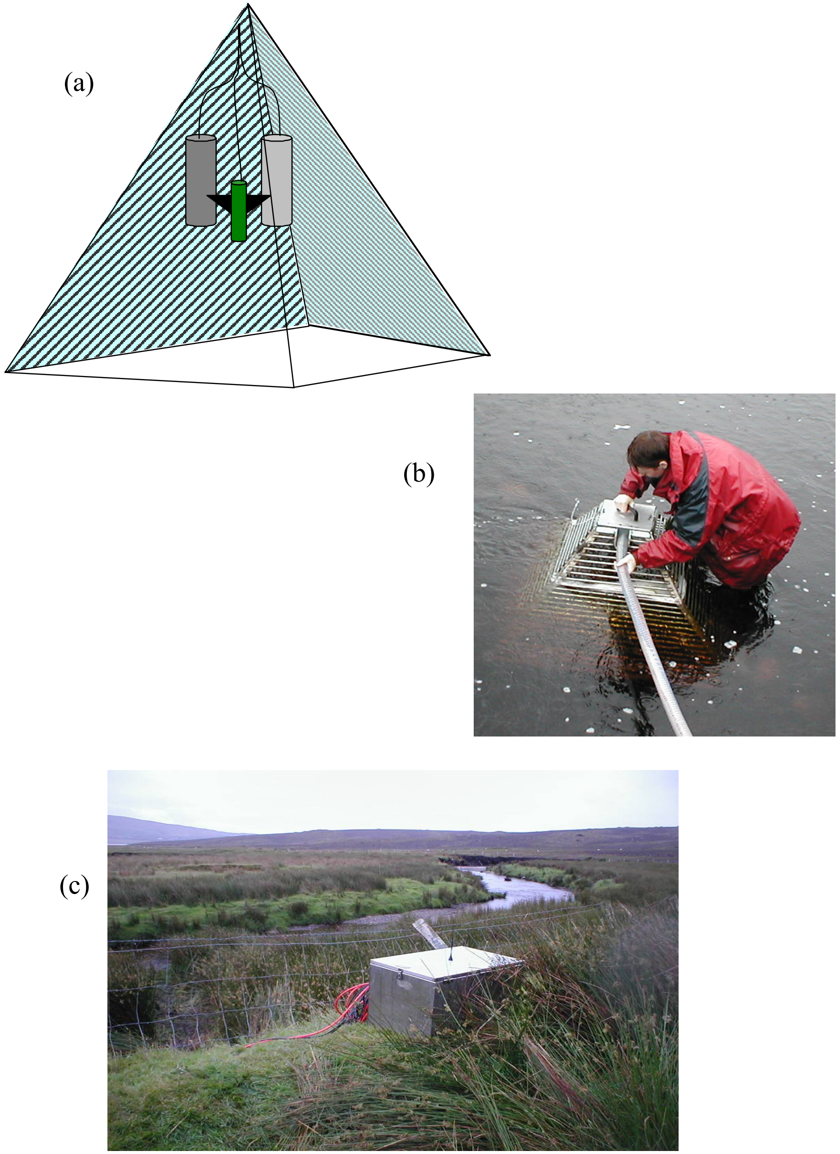


FIG. 2. The 'cage version' of Automatic River Monitoring Station deployed on the Glenamong River, Ireland. (a) schematic diagram of the cage system used to protect the sensors, (b) the cage system *in situ*, (c) the housing of the electronic components.

forestry operations and no risk of damage from floating logs. The electronic components are mounted in waterproof cases that are then housed within a second weatherproof box fabricated in stainless-steel (Fig. 2c). This stainless-steel box also provides electrical screening against possible electromagnetic emissions from the station and reduces its susceptibility to any external electromagnetic interference. The system is powered by two sealed lead-acid batteries which can be exchanged periodically or recharged on-site by a wind generator and/or a solar panel.

Option 2 – abstracting water from the river by a hydraulic ram pump – proved very reliable when tested under controlled conditions, but when deployed in the field it failed to deliver a regular flow of water, this almost certainly being due to interference by passers-by. Option 3 – abstracting water from the river by a mains-powered pump – was used on the Rough and Black Rivers, where it was relatively easy to arrange for mains electricity. The configuration of this variant of the system is shown in Fig. 3, this being practically identical to that used in the system fed by the hydraulic ram pump, except that in the latter system a feeder pipe has to be run upstream to provide the head of water (at least 30 cm) that is required to operate the pump. The sensors are mounted in a sequence of flow cells, which are water- and air-tight. These flow cells are of relatively low volume and are designed to assist the free flow of the sampled water so that 'dead zones' do not develop. In all variants of the system, the sensor for measuring the depth of water consists of a high resolution pressure sensor mounted in the water at a fixed height relative to the stream bed in a 'stilling well'.

The data logger is a Campbell CR10X that stores the recorded data in two 'output areas'. The logger is programmed so that Area 1 is used to store hourly and daily summary data, while Area 2 is used to record high resolution minute-by-minute data. Both 'output areas' operate as circular buffers so that the oldest data in each area are overwritten when that area is full. The logger can store several years of hourly and daily summary data, but memory allocated to the minute-by-minute data is only sufficient to store approximately four weeks of high-resolution data. Much of the time, these minute-by-minute data are likely to be of limited interest, but they could be of great value when they capture an extreme event or during periods of intensive field work.

The Automatic Water Quality Monitoring Stations (AWQMS/AWQMS2)

Two versions of Automatic Water Quality Monitoring Stations, developed from an earlier station (Rouen et al. 2000), were designed for this project. The station deployed on Lough Feeagh in Ireland (AWQMS; Fig. 4a) was a basic unit designed to monitor the thermal characteristics of the lake and the effect of wind-mixing on the horizontal distribution of the suspended sediment. A more advanced station – the AWQMS2 – was also designed, this supporting a fully automatic winch system that enables water quality measurements to be undertaken throughout the water column. Fig. 4b shows the profiling version of the station that was installed on El Gergal reservoir in Spain and used to provide more detailed information on the mixing characteristics of the reservoir. The AWQMS2 also has greater expansion capabilities including the option to duplicate key sensors. This facility was considered vital for 'operational' applications where the reservoir managers need to have complete confidence in the acquired measurements. A number of other modifications to the design of the AWQMS2 units combine to enhance ease of servicing and the safety of personnel visiting the station. For example, the platform is made physically very stable by the addition of a sub-surface structure fitted with counterweights and a more robust handrail bolted to the decking. To simplify servicing, the meteorological sensors fitted to the top of the mast are mounted on a slider mechanism, which allows them to be lowered to a comfortable working height for inspection and/or maintenance.

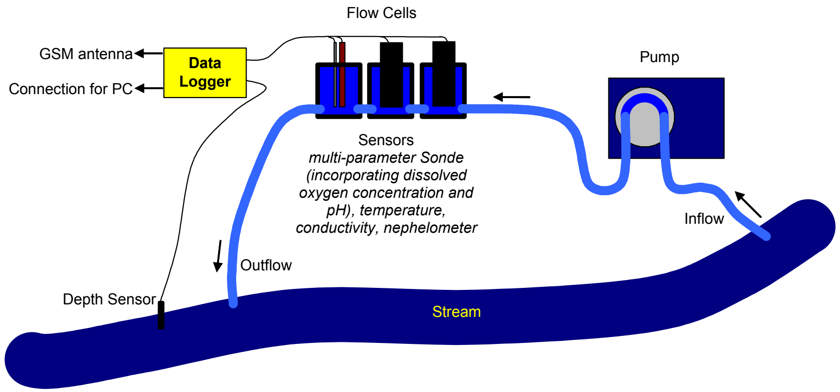


FIG 3. Schematic diagram showing the 'pumped version' of the Automatic River Monitoring Station.

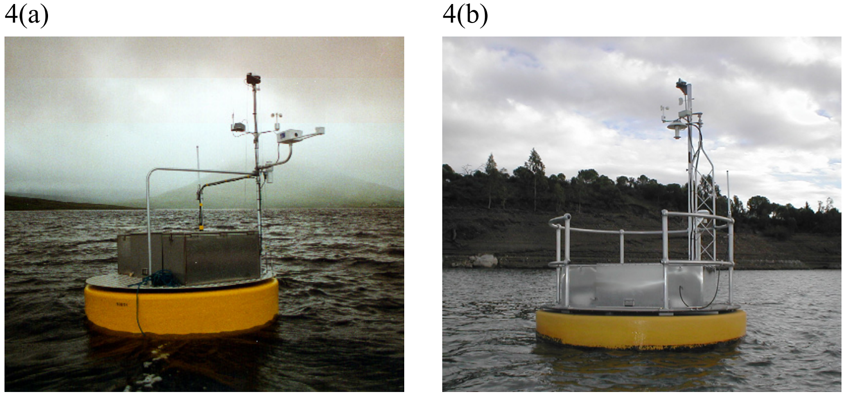

4(a)
4(b)

FIG. 4. (a) The basic Automatic Water Quality Monitoring Station (AWQMS) deployed on Lough Feeagh. (b) The profiling version of the station (AWQMS2) deployed in the El Gergal reservoir operated by EMASESA.

The general configuration of the two versions of lake monitoring station is shown in Fig. 5 and the principal meteorological and limnological parameters measured by the stations are listed in Table 2. In both versions, a toroidal buoy is constructed of closed-cell foam and is fitted with a mast to support the meteorological instruments. Two stainless-steel boxes mounted on the buoy house the control electronics, the data logger, the communication system and the batteries. The data logger used on the basic version of the station is a Campbell CR10X unit with six differential analogue channels and eight digital input/output channels. The profiling version of the station uses a Campbell CR23X which supports twice the number of analogue channels. Both of these data loggers are coupled to expansion modules and custom designed circuitry to accommodate the required additional analogue and digital inputs. All the electronic sub-systems are modular and are housed in waterproof cases that can be exchanged easily on site. Six sealed lead-acid batteries provide the primary source of power for both systems. These can be supplemented by solar cells, although none are fitted as standard. The sealed lead-acid batteries are selected for their suitability to operate over a wide range of temperatures. The state of charge of the batteries is monitored by the data logger. They are exchanged at the normal service interval (monthly) with a second set of batteries, so a total of 12 are required at the site. Batteries are recharged either at the laboratory or at the shore station.

As with the Automatic River Monitoring Station, data are recorded in two 'output areas', allowing high-resolution data to be downloaded following extreme events. Diagnostic and quality control information is also stored along with the environmental data, allowing engineers to confirm the performance of the instruments.

The sensors for measuring the meteorological parameters are commercially available. A magnetic-flux gate electronic compass is used to record the alignment of the buoy and provide the directional information necessary to correct the wind direction measurements. A high-resolution absolute pressure sensor is mounted above water on the buoy to measure barometric pressure. A second absolute pressure sensor is fixed to the lake bed and used to measure the lake level by subtracting the barometric pressure from the readings taken in deep water. Most of the aquatic sensors are integrated in a commercial sonde (a YSI6920 or Hydrolab Quanta) but the system also includes surface and sub-surface photon flux density (PFD) sensors measuring photosynthetically active radiation (PAR). A nephelometer and/or a fluorimeter can also be fitted to enable the concentration of suspended sediment and chlorophyll *a*, respectively, to be determined.

In the basic version of the station, an array of temperature sensors is suspended from the buoy to record the vertical variations in the water temperature. In the profiling version, there is no such array of temperature sensors, but a fully automatic winch. A dedicated microcontroller is used to control the winch to ensure that, in the event of a fault condition, the winch will shut down safely rather than risk damage to a person or equipment.

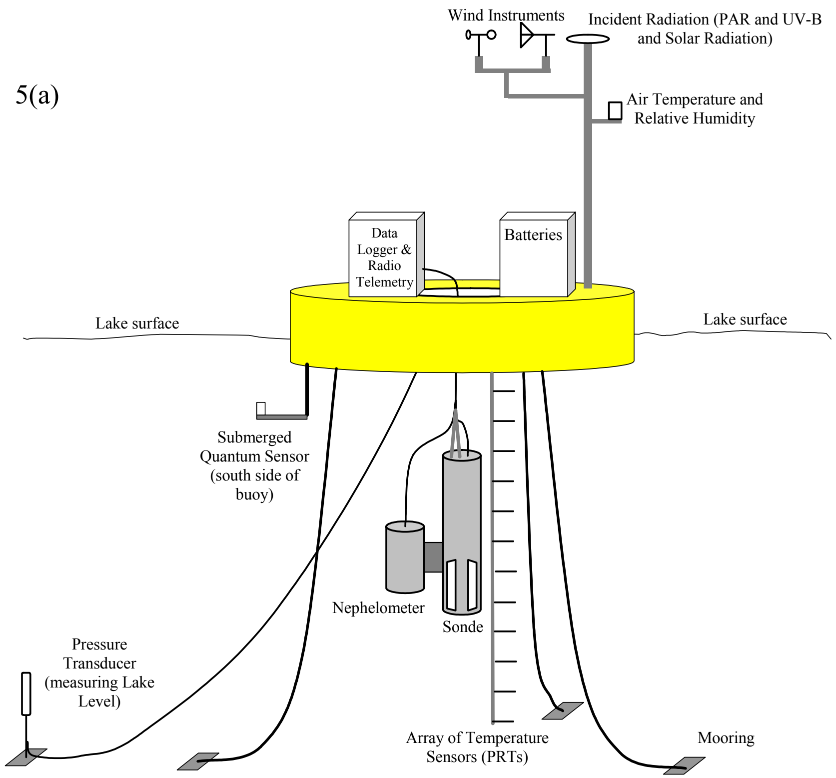
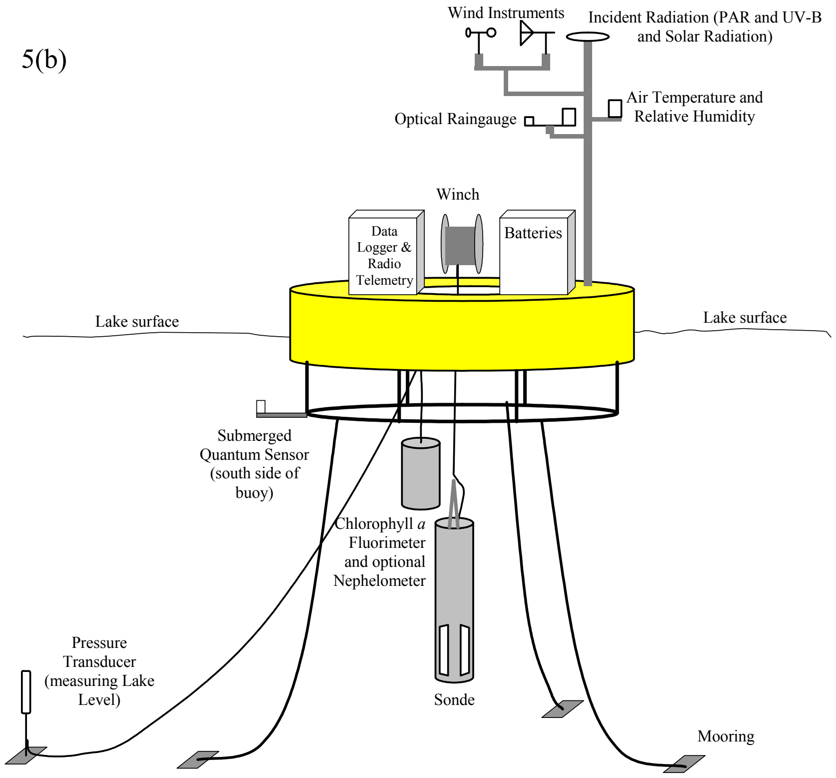


FIG. 5. *(above and opposite)* Schematic diagram showing the general configuration of the two versions of the Automatic Water Quality Monitoring Station: (a) the ‘basic’ version (AWQMS) and (b) the ‘profiling’ version (AWQMS2).



Case studies: some example results from the monitoring stations

The Burrishoole catchment

The Burrishoole catchment is situated a few kilometres from the town of Newport, Co. Mayo, on the west coast of Ireland. A fuller description of the Burrishoole system is given by Allott et al. (2005, this volume) and May et al. (2005, this volume). In recent years, the combined effects of extreme weather events and heavy grazing have resulted in a marked increase in the quantity of peat eroded from from the surrounding land. The erosion of peat is minimal on land that has an intact vegetation cover but the loss of vegetation exposes more of the soil, increases the rate of runoff

Table 2. The principal sensors supported by the two versions of Automatic Water Quality Monitoring Station (AWQMS and AWQMS2).

PARAMETER		SENSOR TYPE	QUANTITY		RANGE
			AWQMS	AWQMS2	
Water Quality	Water temperature	Platinum resistance sensor (PRT)	1	2	-5 to +40 °C
	Water column stability	Array of platinum resistance sensors (PRT)	1	1	-
	Dissolved oxygen concentration	Polarographic cell	1	2	0 to 500 % air saturation
	pH	Glass combination electrode	1	2	2 to 14 pH units
	Conductivity	4 electrode cell	1	2	0 to 100 mS cm^{-1}
	Light extinction (PAR)	Pair of photodiode based quantum light cells (surface and submerged)	1	1	0 to 2500 μE m^{-1} s^{-2} 0 to 100 %
	Water level	Semiconductor strain gauge	1	1	0 to lake depth
	Chlorophyll *a*	Fluorimeter	0	1	Dependent on algal composition
	Suspended sediment	Nephelometer	1	1	Dependent on sediment composition
Meteorological	Aspirated air temperature	Platinum resistance sensor (PRT)	0	1	-40 °C to +60 °C
	(Non-aspirated) Air temperature	Platinum resistance sensor (PRT)	1	2	-40 °C to +60 °C
	Relative humidity	Semiconductor sensor	1	2	0 to 100 %
	Wind speed	Cup anemometer	1	2	0 to 50 m s^{-1}
	Bearing	Flux gate compass	1	1	0 to 360°
	Wind direction	Wind vane	1	1	0 to 360°
	Solar radiation	Pyranometer	1	0	0 to 2000 W m^{-2}
		Net Radiometer (long and short wave upwelling and down-welling radiation)	0	2	0 to 2000 W m^{-2}
	Incident PFD (PAR)	Quantum light cell	1	1	0 to 2500 μE m^{-1} s^{-2}
	Incident UV-B light	UV-B cell, photodiode based	1	1	-
	Atmospheric pressure	Semiconductor strain gauge	1	2	0 to 2000 mBar
	Rainfall	Optical rain gauge	0	1	-

and leads to increased rates of erosion. These erosion rates are, however, highly variable and are strongly influenced by the frequency as well as intensity of heavy rain. Automatic instruments that can be deployed on site to monitor the impact of these extreme events provide an ideal means of quantifying these complex responses.

Fig. 6 shows some example results from the ARMS station located on the Rough River together with rainfall data from the corresponding period. The Rough River is a tributary of the Black River and its catchment drains the hillsides on the eastern side of the Burrishoole system. The upper reaches are quite steep and the river usually responds quite quickly to

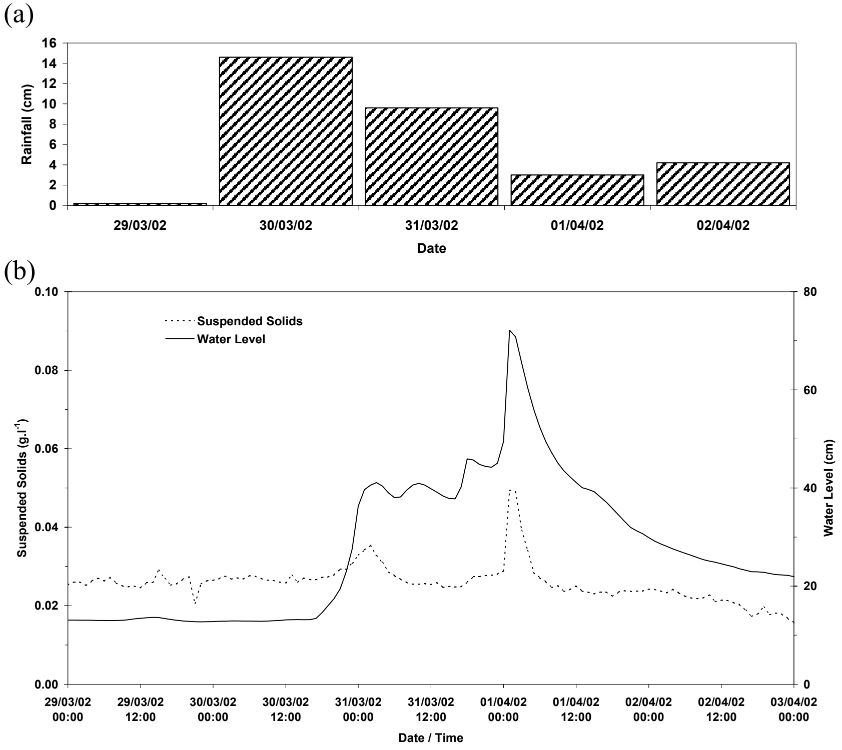


FIG. 6. Some example results from (a) an automatic rain gauge in the Rough River sub-catchment and (b) the ARMS station on the Rough River. The water level and suspended sediment data were acquired between 29 March and 2 April 2002 and are the hourly averages stored by the data logger. The rainfall values are daily averages and were measured by a recording rain gauge located about 30 m away from the river station.

rainfall events. Prior to 1996, 95 % of the catchment was forested, but since then approximately 50 % of the trees have been harvested and replanted.

The results demonstrate the effect that a relatively modest increase in the rainfall had on the water level in the river and the downstream transport of sediment. At the beginning of the period shown, very little rain had fallen during the previous 18 days. The first day of heavy rain (30 March 2002) produced a sharp increase in the water level and a brief ‘pulse’ of sediment, but the most pronounced increase in the sediment load was not recorded until 1 April resulting from further intense rainfall which also further raised the water level. Delayed responses of this kind are commonly recorded in afforested catchments when the weather has been dry for some time (Mills 1991). Peaty soils are slow to drain, but once the soil is saturated substantial quantities of water and soil can be channelled though any drainage ditches present.

The impact of this ‘threshold’ effect on the downstream transport of sediment becomes even clearer when we examine the high-resolution measurements recorded by the ARMS in the early hours of 1 April. Fig. 7 shows the minute-by-minute variations in the water level and suspended sediment concentration recorded by the data logger over this critical period. Although the mean concentration of sediment recorded in the river during this event was rather low (ca. 0.04 g l^{-1}) there is a very close temporal correlation between the recorded concentrations and the flood hydrograph.

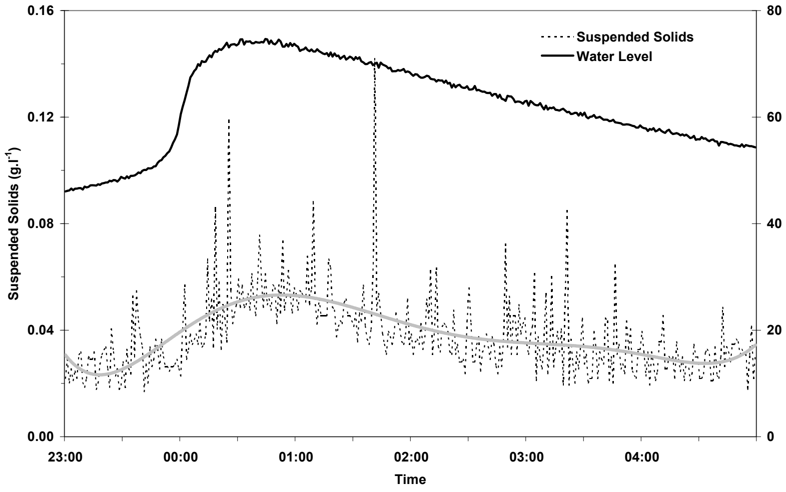


FIG. 7. The high-resolution measurements recorded by the ARMS station on the night of 31 March / 1 April 2002.

El Gergal reservoir

El Gergal is the last in a series of reservoirs managed by the Spanish water company, EMASESA (Empresa Municipal de Abastecimiento y Saneamiento) to supply water for the city of Seville. The quality of the water stored in the reservoir is generally very good but increased operational costs are often incurred in summers when the water level is low. A more detailed description of El Gergal is presented by Cruz-Pizarro et al. (2005, this volume).

The example measurements presented in Fig. 8 demonstrate one of the ways in which high-resolution automatic monitoring systems can revolutionise the way in which we manage a reservoir of this kind. They are taken from an intensive study of the impact of water abstraction on the physico-chemical structure of the water column, where short variations in the structure can have a significant effect on the quality of the abstracted water. The mid-water reduction in the oxygen concentration is rather unusual and could be related to the very rapid discharge of water from the reservoir at the time of measurement. Detailed profiles of this kind are of great interest to the reservoir managers who can then modify the operational regime to optimise the quality of the abstracted water. These measurements were recorded fully automatically by the profiling Automatic Water Quality Monitoring Station (AWQMS2) using a YSI6920 sonde fitted to the automatic winch.

In El Gergal, some of the most serious water quality problems encountered in recent years have been associated with the accumulation of algae in certain parts of the reservoir. When the wind speed is low, buoyant algae such as bloom forming cyanobacteria float to the surface and accumulate downwind. Automatic stations, like the AWQMS2, can record not only the weather events responsible for these accumulations but can also monitor the short-term variation in the biomass of the drifting plankton.

Fig. 9 shows the results of an analysis where the short-term variation in the biomass of phytoplankton drifting past the buoy is used as a daily measure of the wind-induced patchiness. In this figure, the coefficient of variation (standard deviation/arithmetic mean) of the hourly chlorophyll *a* measurements recorded by the AWQMS2 is used as a proxy of this spatial variation. The wind speeds in the figure are the daily means measured by the same station. The results demonstrate that local patches of phytoplankton tend to appear when the wind speed is relatively low. A short period of high spatial variation was recorded in mid-July but the most

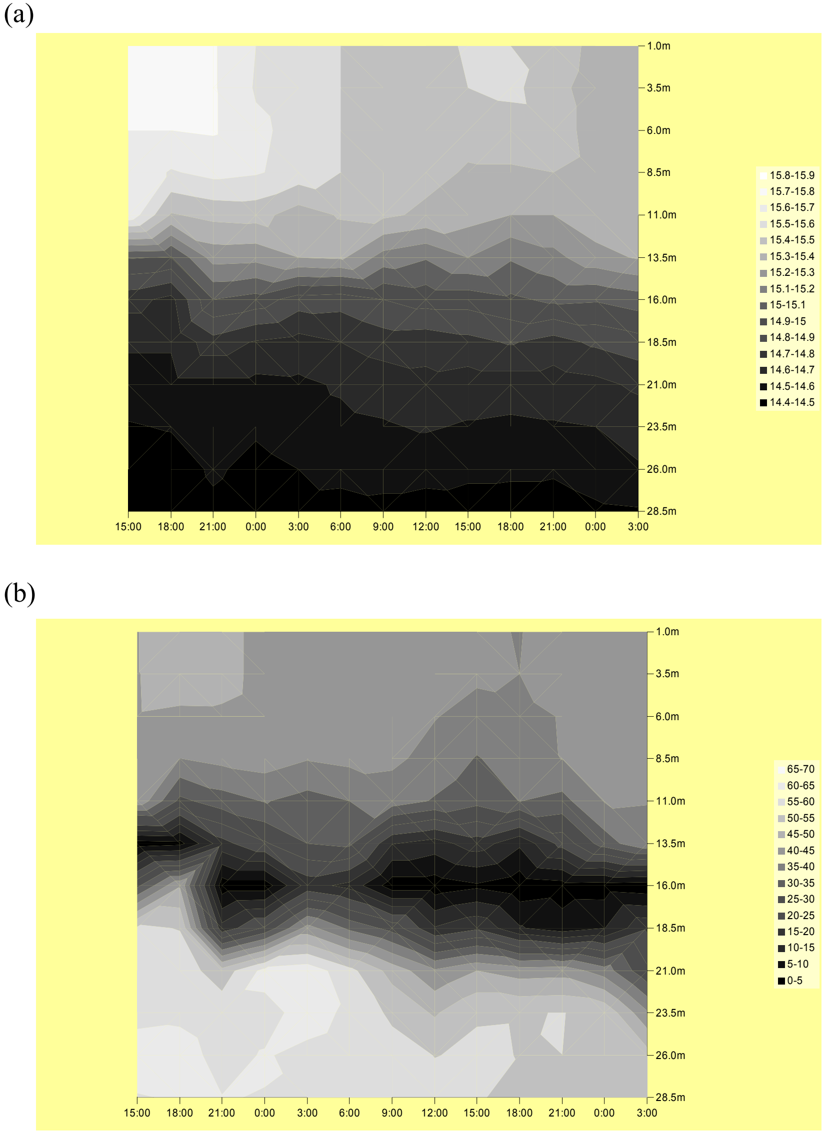


FIG. 8. Contour diagram showing vertical variations in (a) temperature (°C) and (b) dissolved oxygen concentration (% saturation) in El Gergal recorded by the Automatic Water Quality Monitoring Station (AWQMS2) over a 36-hour period from 15:00 on 29 November to 03:00 on 1 December 2002.

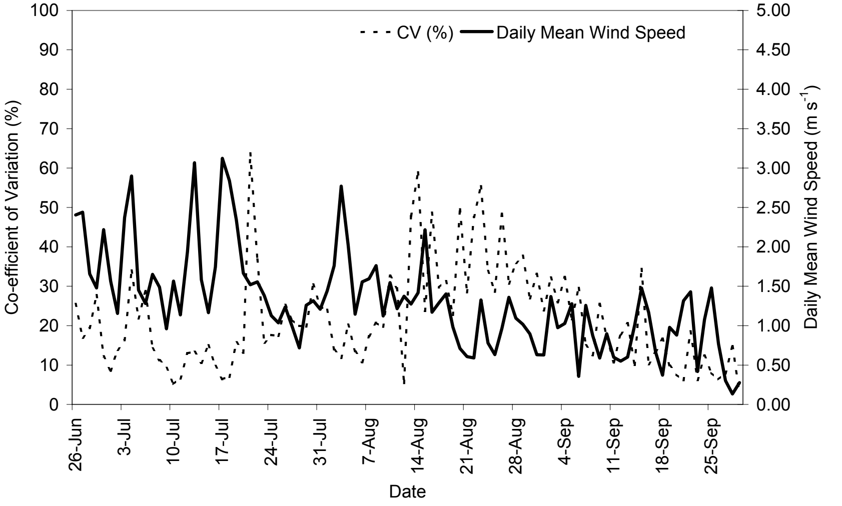


FIG. 9 Comparison of the short-term variation in the biomass of phytoplankton (as a measure of algal patchiness) with the mean wind speed over El Gergal.

prolonged period of spatial heterogeneity was that recorded during the blue-green algal bloom in early August. Local accumulations of this kind can have a serious effect on the quality of water abstracted from the lake. In Fig. 9 we have only presented information on the average wind speed, but the wind-direction data recorded by the AWQMS2 can also provide useful information on the spatial distribution of the algal patches.

Concluding remarks

From a technical point of view, the most important features of the automatic monitoring stations were their overall reliability, the sophistication of the self-diagnostics and the versatility of the assembled components. A significant portion of the design effort was devoted to ensuring optimal reliability of the systems when exposed to hostile environmental conditions. All the electronic components are rated to 'industrial' temperature specifications (i.e. rated for operation at temperatures down to -25 ºC). Attention has also been paid to minimising the impact of any potential faults that could occur in a particular sensor or sub-system. For example, supplies to each sensor are monitored and can be switched on or off either automatically by the data logger or through a command issued by an operator at a remote location. The lake/reservoir monitoring stations incorporate sophisticated self-diagnostic features that provide quality assurance data as well as system performance records. The engineers at Windermere were able to contact the stations via the telemetry to investigate any suspected sensor or system malfunction and were then able to suggest remedial measures to local, non-technical staff. The lake/ reservoir stations can be easily expanded and can support almost any sensor that can be powered from a 12V supply.

We have shown how catchment and reservoir management can be greatly enhanced by reliable, high-resolution monitoring instruments, such as those described here. Elsewhere in this volume, the application of these measurement technologies are described in some detail. The integration of the high-resolution monitoring and the process-based modelling demonstrate how our scientific understanding of these complex systems can be best advanced by the close collaboration of engineers, technologists and scientists.

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