

## Autonomous profiling device to monitor remote water bodies

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*In tropical climates, most freshwater reservoirs, dams and lakes are prone to annual summer stratification during which bottom water layers near the bed become hypoxic (< 2 ml/l) with very low concentrations of dissolved oxygen (DO). This has serious implications to human health, and requires frequent and effective monitoring, particularly during summer months (March–May) when water consumption is highest. These water bodies are frequently located in remote areas away from human habitation, making it logistically difficult to access and monitor their water column properties on a regular basis. The need for monitoring temporal changes in freshwater ecosystems is addressed in this note through the description of a patented technology – Autonomous Vertical Profiler (AVP) designed and developed at the National Institute of Oceanography (NIO), Goa, for use in both coastal and freshwater bodies. The AVP was used in experiments to satellite transmit complete time and location referenced high-resolution profiles of temperature, phytoplankton concentration, turbidity and DO from the remote Tillari Dam – a freshwater reservoir near Dodamarg, Maharashtra, India. The profiles were received without errors at the Marine Instrumentation Laboratory at NIO. The benefits of in situ time-series profiling with AVP captured the onset of developing hypoxia in early April 2011 over a 9-day unsupervised profiling experiment. A similar 5-day experiment in February 2011 tracked diurnal changes in phytoplankton concentrations through night and day, suggesting a possible interplay between recycled production and photoinhibition.*

The conventional approach to profile the water column is by the collection of water samples using a rope and weight to trigger a Niskin sampler positioned at a selected depth. The sampled volume of water is then hauled up with a rope for fixing and storage in glass bottles, with all such operations carried out on a small boat in the reservoir. The process is repeated to different depths so as to populate the profile with more data points. The water flasks are stored with care for transportation to the laboratory for subsequent analysis of the concentration of dissolved oxygen (DO), nitrates, nitrites, turbidity, chlorophyll and other nutrient parameters. It is clear that the conventional approach is labour intensive, time-consuming, and suffers from gross under-sampling in space and time.

An attempt to introduce more sophisticated technology to profile the water column was made by Desa *et al.*<sup>1</sup> using a small Autonomous Underwater Vehicle (AUV) *Maya* to detect hypoxia, in the Idukki Reservoir in Kerala, India. The hypoxic effect was detected during two successive years, 2006 and 2007, during May when stratification sets in. The technique of staircase diving the AUV was used to recover the profile of DO, temperature, and turbidity and phytoplankton concentration. The advantage of using small AUVs is that it provides spatial variation of these variables

in two dimensions at any selected depth. However, the uneven bottom topology of Idukki Reservoir and the logistics to operate AUVs in confined spaces make it impractical for use on a routine basis. What is needed is a profiler that can vertically transect the water column of a reservoir as close to the bed while acquiring and storing data during its descent.

The availability of new robust wet sensor technologies, low power embedded controllers, programmable motors and micro satellite transceivers has made sensor-based oceanography a reality at affordable cost. In this note we present a brief description of a patented robot profiler<sup>2</sup> – the Autonomous Vertical Profiler (AVP) that meets the requirements of rapid, high resolution, repeatable profiles with unsupervised satellite transmission of acquired sensor data to a shore laboratory. The AVP was used in two long-term (9-day and 5-day) unsupervised experiments at the Tillari Dam – a large freshwater reservoir in Dodamarg, Maharashtra, India. *In situ* profiles of temperature, chlorophyll, turbidity and DO from the surface to 40 m depth from a tethered AVP were beamed back by a satellite link to the National Institute of Oceanography (NIO) Laboratory at Goa, situated 50 km from Tillari. The time series profiles of February 2011 present the picture of a stable ecosystem, well-oxygenated

water column with constancy in measured variables over a 5-day period. In contrast, the April 2011 experiment captures the onset of increasing hypoxia from the bottom layers of the Tillari Reservoir, a mid-water layer of low turbidity located below a surface layer of phytoplankton over 9 days. In the section that follows, we present a short description of AVP, the experimental set-up at the Tillari Reservoir where the time series experiments were conducted and a discussion on a possible explanation of the water-column data.

### Background on *in situ* profilers

The best known method of profiling the properties of the ocean water column is the Conductivity–Temperature–Depth (CTD) system used widely in most modern oceanographic vessels. In these systems, CTD and other oceanographic sensors are mounted beneath a water-sampling rosette ensemble, all of which can be lowered from the hydrographic winch on the ship. As the system moves through the water column, sensor data are transmitted through the winch wire to a shipboard data logger, which also controls the sequence of closures of the sampling bottles on the rosette and the storage of data. These devices are large, cumbersome and expensive to operate at

sea, and in addition, face the problem of the motion of the ship being coupled into the winch wire thereby possibly affecting the measurement process.

Early oceanographic profilers were first designed to measure ocean current flows. A variety of forms have evolved over several decades starting in 1965 with the free-drop technique used by Richardson and Schmitz<sup>3</sup>, then the wire guided profilers of Duing and Johnson<sup>4</sup>, the bottom-mounted, winch-based profiler of Walden and Collins<sup>5</sup>, the cyclic profilers by Honji *et al.*<sup>6</sup> and the Cartesian diver of Duda *et al.*<sup>7</sup>. A more recent wire-guided walker uses ocean wave energy to drive a buoyant, instrumented platform down a wire from a surface float<sup>8</sup>. A cam that rectifies vertical motion is released when the wire walker hits a mechanical stop, after which the wire walker floats to the surface. Portable winch-operated profilers have been developed for estuarine applications<sup>9</sup>, but these are cumbersome and outdated systems. More recent research developments reported have been on shallow-water buoyancy driven Lagrangian floats profiling at speeds of 0.3 m/s, but with settling times of the order of tens of seconds and operating within a large range of sea-water densities<sup>10</sup>. However, the inherent limitation of all buoyancy-driven systems is that they are too slow to match the requirement for rapid profiling of repeated dives in shallow waters.

**Autonomous vertical profiler**

The concept of AVP was first proposed by Desa *et al.*<sup>2</sup> (US Patent No.: 6786087). The AVP is a robot profiler that is propelled downwards through the water column by a DC thruster while sensing and storing the vertical structure of water properties as a function of depth. The profiler can be programmed to descend to a given depth set by the user, while its ascent to the surface is without propulsion, as it is positively buoyant. On breaking the sea surface, the AVP transmits its Global Positioning System (GPS) coordinates, measured sensor data and vehicle parameters via a satellite modem. A time series of repeat dives at a fixed location and at set intervals can be built up to monitor temporal changes in the ecosystem variables through the day and night over several days.

*Physical description*

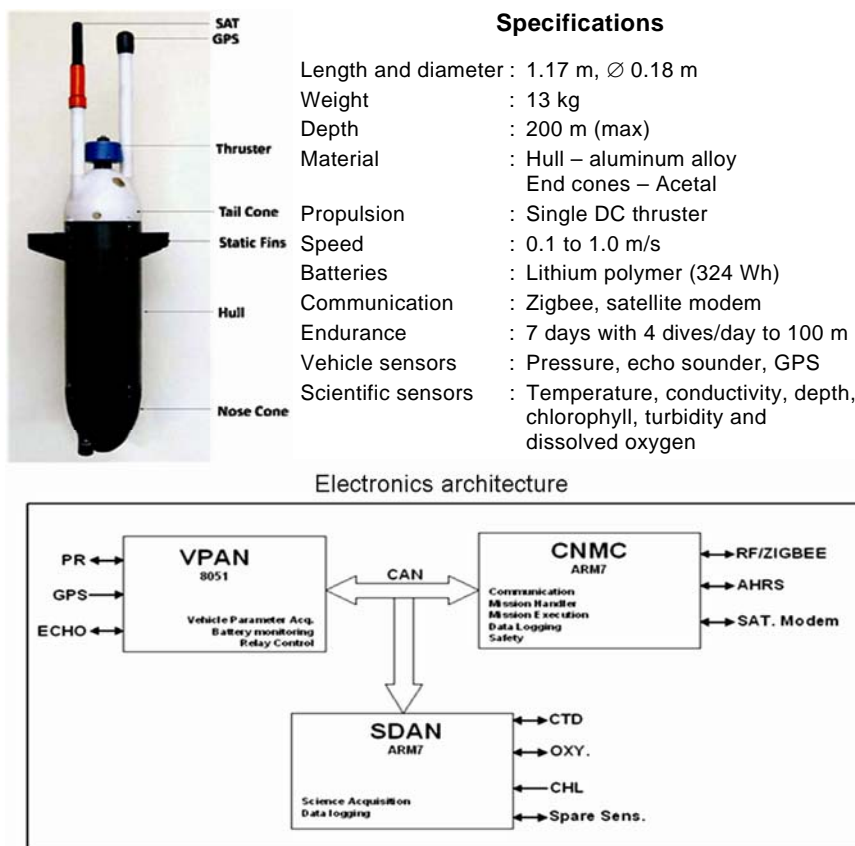
The AVP (Figure 1) consists of three parts, namely (i) the nose cone (ii) the main hull and (iii) the tail cone. The nose cone is free-flooding, i.e. it permits water to enter as the sensors in the nose are water-tight and pressure-proofed, and machined from an Acetal SA 550-grade cylinder. It accommodates a digital echo sounder, temperature, chlorophyll, turbidity and oxygen sensors. The main hull is made from an open cylindrical aluminum alloy tube section and contains the electronics and the batteries. The hull is sealed at both ends with removable aluminum alloy end-plates. The hull assembly has been pressure-tested in a pressure chamber to 300 m. The tail cone of AVP is also free-flooding and is fixed on the rear end-plate. It serves the purpose of gripping the thruster body, of accommodating pressure-proof foam for extra buoyancy and also provides a means of locating the GPS and satellite antenna stubs through it. The system has been designed to have a large separation

between the centre of buoyancy (Cb) and the centre of gravity (Cg), which helps keep AVP stable and vertical in orientation before a dive.

*Sensors used on the AVP*

*Sensors:* The specifications of sensors used on AVP are listed in Table 1, showing range, accuracy and maximum sampling rate. The sensors include an active fluorometer (EcoPuck Wetlabs, USA) that measures chlorophyll and turbidity simultaneously in one underwater package, a fast dissolved oxygen sensor (RINKO III, Japan) and CTD (FSI, USA). Most of the science sensors, including the pressure sensor, are located within the nose cone (Figure 1). The CTD, due to its larger size, was secured externally to the ribs of AVP near the nose cone.

*Combination sensors of chlorophyll and turbidity:* Chlorophyll *a* molecules in phytoplankton cells floating in the water



**Figure 1.** (Top) Photograph of the Autonomous Vertical Profiler (AVP) and its main specifications. (Bottom) Distributed architecture of the electronics using three microcontrollers to share the tasks and control the functions of the AVP.

column emit red fluorescence (at 685 nm) when irradiated with monochromatic blue light. The chlorophyll *a* fluorescence signal is received by a silicon photodiode inside the instrument casing after excitation by two high-brightness LEDs at 455 nm modulated at 1 kHz, and launched at an angle between 55° and 66° through the optical window on the end-plate of the sensor. The photodiode is positioned to receive fluorescence at a backscattered angle of 140° formed by the intersection of the field-of-view (FOV) light cones of the emitters and the detector. In practice, the intensity of red fluorescence increases nonlinearly with an increase in the concentration of chlorophyll.

Turbidity gives a measure of the light scattered by all suspended particles in a solution and is expressed in nephelometric turbidity units (NTU). The suspended matter can include mud particles, sand, clay, submicrometre detrital particles of organic origin, plankton bacteria, faecal matter and other microscopic organisms. In the EcoPuck, the same detector that is used to measure chlorophyll fluorescence is used to receive backscattered flux from an angle of 140°, but emitted by a different LED at 700 nm. In practice, the turbidity signal is also used to correct for the fluorescence signal. Water samples for the independent estimation of chlorophyll were collected at depths determined from the AVP profiles. Following well-known procedures of filtration, acidification and extraction of pigments from acetone, the chlorophyll *a* concentration ( $\text{mg}/\text{m}^3$ ) was determined by HPLC analysis, which was used to calibrate the fluorometer sensor values of chlorophyll.

**DO sensor:** The DO sensor (RINKO III, Japan) used on AVP, like the EcoPuck, is an optics-based sensor. It is based on the decay time of phosphorescence. The optical window on the sensor exposed to the surrounding water is coated with a layer of pressure-sensitive paint (PSP) having phosphorescent properties. When a pulse-excitation light emitted from inside the sensor casing irradiates the PSP material, it interacts with oxygen molecules in its excited state losing energy via phosphorescent pathways with an intensity that is negatively correlated with oxygen partial pressure, being highest at anoxic concentrations of oxygen. The response time of

the sensor is less than 1 s better than most existing commercial DO sensors having typical response times of ~ 25 s or more. The technique does not consume oxygen molecules, is not affected by ambient sunlight, shows stability at high pressure, and is linear with DO concentration (Table 1). The calibration method used here is similar to the *in situ* approach used in estimating fluorometric chlorophyll. Water samples were collected at two shallow water stations off Goa (west coast of India) and the concentration of DO ( $\mu\text{M}$ ) determined by the standard Winkler titration technique. In Figure 2, independent measurements of DO ( $\mu\text{M}$ ) from water samples (shown as

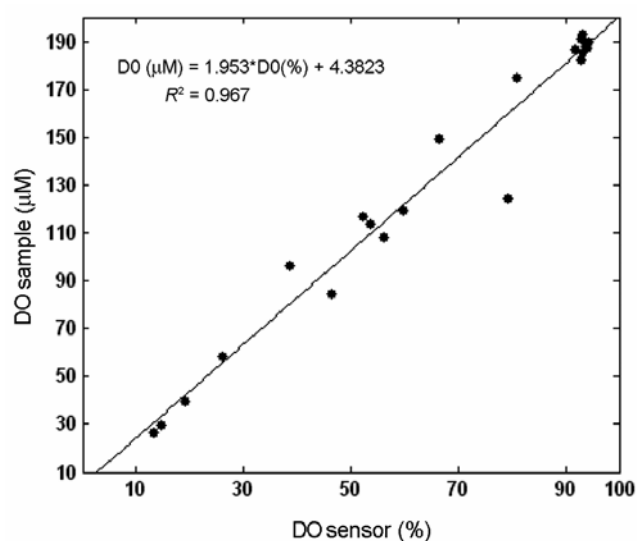
solid circles) are plotted versus the corresponding DO sensor output (corrected for temperature and depth effects) in percentage of saturation derived from depths selected from the AVP profiles. Figure 2 shows excellent linearity with a high correlation coefficient of 0.967.

### Electronics architecture

The electronic architecture of AVP is based on two ARM7 processors, namely (i) Communication Navigation and Mission Controller (CNMC), Science Data Acquisition Node (SDAN), and (ii) a Vehicle Parameter Acquisition Node

**Table 1.** Sensors used on the Autonomous Vertical Profiler and their specifications

Sensor	Range and accuracy	Sampling	Response time
Dissolved oxygen	0–200% 00 $\mu\text{M}$ Linear $\pm$ 2% FS	1 s to 255 min (1 Hz in AVP)	~ 1 s
Chlorophyll	0.02–60 $\mu\text{g}/\text{l}$	~ 8 Hz (4 Hz in AVP)	< 125 ms
Turbidity	0–25 NTU	~ 8 Hz (4 Hz in AVP)	< 125 ms
Conductivity	0–90 mS/cm ( $\pm$ 0.002 mS/cm)	~ 8Hz (4 Hz in AVP)	< 95 ms
Temperature	–5–45°C ( $\pm$ 0.005°C) (Accu)	~ 8Hz (4 Hz in AVP)	< 100 ms
Depth	0–740 dbar ( $<$ 0.08% FS)	~ 8Hz (4 Hz in AVP)	Instantaneous



**Figure 2.** *In situ* calibration plot comparing dissolved oxygen (DO) sensor output (saturation percentage) with DO ( $\mu\text{M}$ ) measured from water samples by Winkler titration method at the same ship location.

## TECHNICAL NOTE

(VPAN) communicating internally over a Controller Area Network (CAN) interface, as shown in Figure 1.

The VPAN node handles data acquisition from vehicle sensors, the GPS receiver, echo sounder and pressure. Additionally, the node monitors the battery voltage of thruster and electronics payloads. The major tasks handled by CNMC are that it gets data from the sensors and logs them in the form of files onto the SD card as a backup. It logs vehicle parameters such as battery voltage, depth, position from GPS and control voltages during the dive. A separate file is created in which it stamps the science parameters for every 1 m of the dive. The same file is used to send the data through the satellite link.

A user-friendly Graphical User Interface (GUI) using LABVIEW has been developed for mission programming, vehicle data monitoring, data acquisition and downloading. The GUI is loaded on a notebook and interacts with AVP through a radio modem connected to a serial port. When AVP is on the surface, full system status and vehicle data are updated and displayed every 5 s with appropriate warnings. In addition, the GUI also displays: (i) the link status between AVP and PC, AVP position and sensor status; and (ii) time for a mission to start, AVP status after a dive, battery voltages and memory status.

The CNMC logs all the vehicle parameters and additionally logs science data as a backup to the science node. The science node is responsible to initialize, acquire, store as well as transmit the data received from DO, temperature, chlorophyll and turbidity sensors to CNMC over the CAN network. On resurfacing, the AVP powers ON the satellite modem, checks the signal strength and uploads the file. The data are transmitted as fixed-sized multiple messages using the short burst data (SBD) transmission mode. The uploading then takes place by breaking the file in frames of 262 bytes. The frames are appended with start-of-frame (SOF) and frame number, which would enable the land station to reconstruct the file. The frames of 270 bytes are uploaded in the form of short message service (SMS) in binary form.

### Experimental set-up at Tillari Dam

The experiments were conducted at Tillari Dam, one of the larger earthen

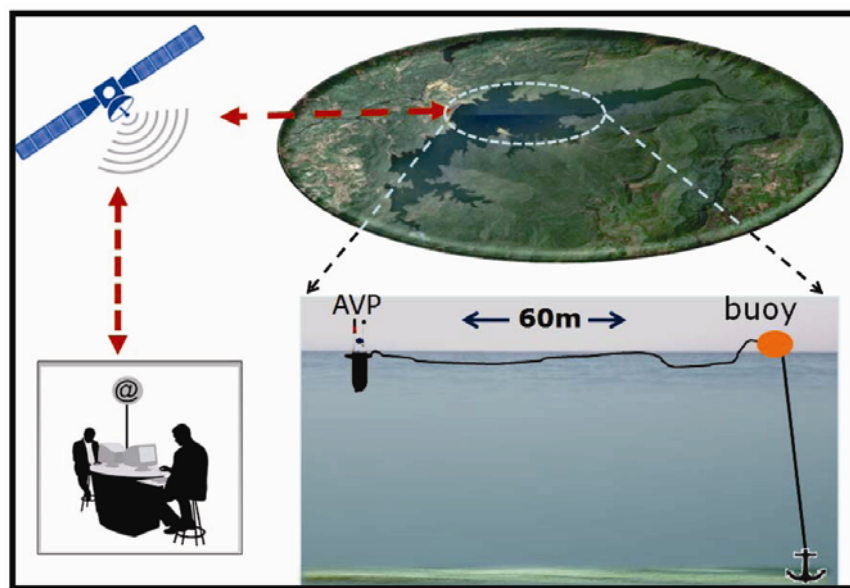
dams in India. It supplies close to 100 million litres of water per day to Bicholim, Assonora and Pernem talukas in Goa for drinking and irrigation purposes. The Tillari Reservoir was chosen as it has sufficient water depth (~50 m) all the year round, and is remote enough from the NIO Laboratory, yet logistically close enough for deployment, retrieval and testing (Figure 3).

### Deployment

A rapid echo-sounder survey of the dam was first carried out to find a location having suitably large depth of ~40 m for the AVP dives. In order to prevent AVP from drifting because of wind action when it is on the surface, it was necessary to secure it to a long nylon rope of ~60 m (~1.5 × water depth) attached to an iron weight resting on the reservoir bed. A marker buoy with a chain resting on the seabed was attached to anchor weight. This arrangement served to mark the AVP site (right panel, Figure 3). The safety aspects built into the system include bottom collision avoidance with inputs from the echo sounder, depth cut-off with pressure sensor inputs, mission timeout and low battery voltage cut-off. In case any of these conditions are met, AVP is programmed to cut-off the motor input and rise to the surface with the built-in positive buoyancy.

### Unsupervised environmental monitoring using satellite links

The aim of the experiment was to demonstrate the feasibility of environmental monitoring of water reservoirs/dams or the coastal seas through time series profiling of the water column and the transmission of such profiles via satellite to a shore laboratory (Figure 4). AVP was interfaced to a commercially available satellite transceiver so that acquired profiles could be transmitted and received on the GUI running on a user computer at NIO. The protocol adopted was to program AVP to dive to a depth of 40 m repeating the dive four times a day at 6 h intervals and as long as the batteries permit. At the start of a dive, AVP is oriented vertically (as shown in Figure 1) with sensors on the nose cone fully immersed in water, thruster in the rear cone just immersed and the antenna protruding out of the water surface. When the motor is turned on, it propels AVP vertically downwards. The sensors in the nose cone are the first to sample the approaching undisturbed water layers which are not yet exposed to the churning by the propeller blades of the thruster. Thus only sensor data from downward dives are used for analysis, as data from the ascent of AVP would be first disturbed by the thruster and antenna assembly. At the end of the dive, time and date stamped profiles of temperature, chlorophyll, turbidity and DO



**Figure 3.** The AVP tethered to an iron anchor on the reservoir bed by a thin nylon rope. A marker buoy acts as a site locator. Satellite transceiver fitted on the AVP can send data or receive commands to alter mission scripts.

are transmitted at a lower 1 m resolution to reduce the file size and satellite transmit time. The actual acquired profiles are stored at a higher 10 cm resolution on the flash memory on AVP electronics. In addition, the user receives hourly updates of the AVP status at the site containing GPS coordinates, date, time and battery voltage levels.

## Results and discussions

The AVP was deployed in the tethered configuration (Figure 3) at the Tillari Dam in two separate experiments during early February and late March 2011.

### Five-day time series experiment (10–15 February 2011)

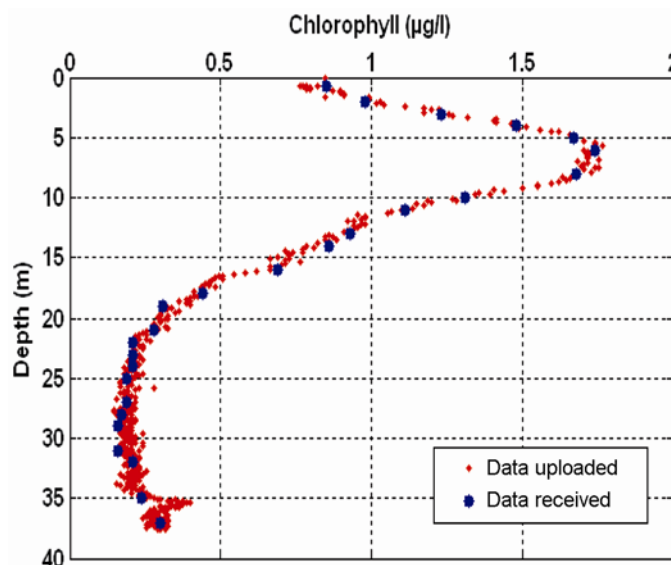
The first experiment lasted for 5 days starting at 12:00 h on 10 February to 15 February 2011, with dives spaced out at 6 h interval starting with the first dive at noon (12:00 h) on 10 February 2011. The mission program was downloaded to AVP at the experimental site. Thereafter, downcast profiles of chlorophyll, turbidity, DO and temperature to a depth of 40 m were received by the satellite link at the NIO Laboratory 50 km away from Tillari. All 19 profiles of the four sensor variables are shown in Figure 5.

### Observations of 5-day round-the-clock profiling

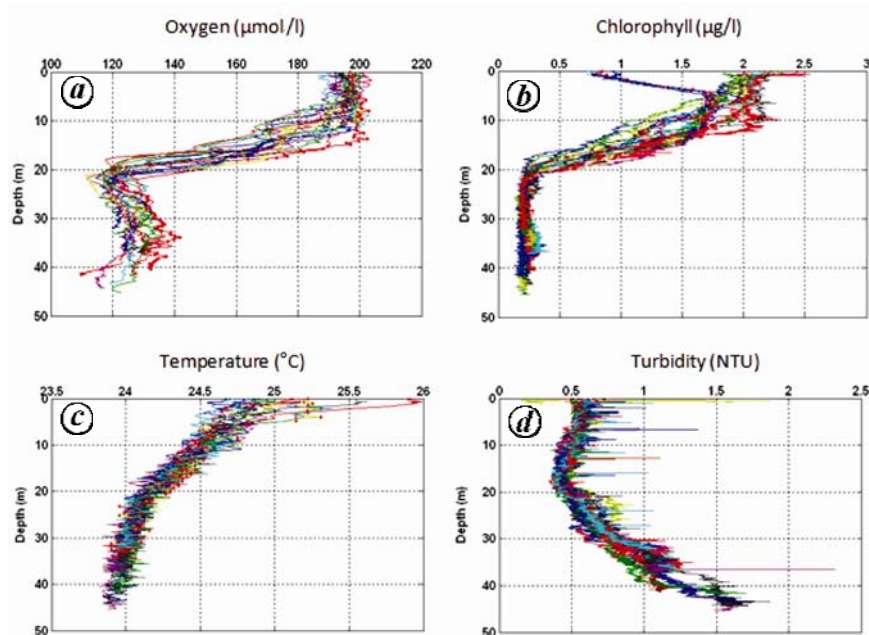
The repeatability in the shape of the vertical structure of the variables chlorophyll *a*, turbidity, DO and temperature suggests low variability over the 5-day monitoring period in the Tillari Reservoir ecosystem. This is not surprising as the only driving forces are wind acting on the surface and solar radiation during the day. Small effects from bottom currents resulting from the release of water during the day can be neglected. In comparison, coastal waters are subject to upwelling currents, solar radiation, tidal and coastal currents, winds and waves. The relative high values of DO (200  $\mu\text{M}$ ) at the surface and 120  $\mu\text{M}$  between 20 and 40 m suggest reasonable oxygenation of waters in the hypolimnion (Figure 5a). The chlorophyll maximum varies, but remains mostly constant in the 5 m

surface layer (Figure 5b). The temperature profile shows a shallow mixed-layer stratification, with a drop from the surface value of 26°C to  $\sim$ 24°C at 30 m and beyond. Turbidity as measured by the EcoPuck sensor configuration provides a backscattering estimate from all

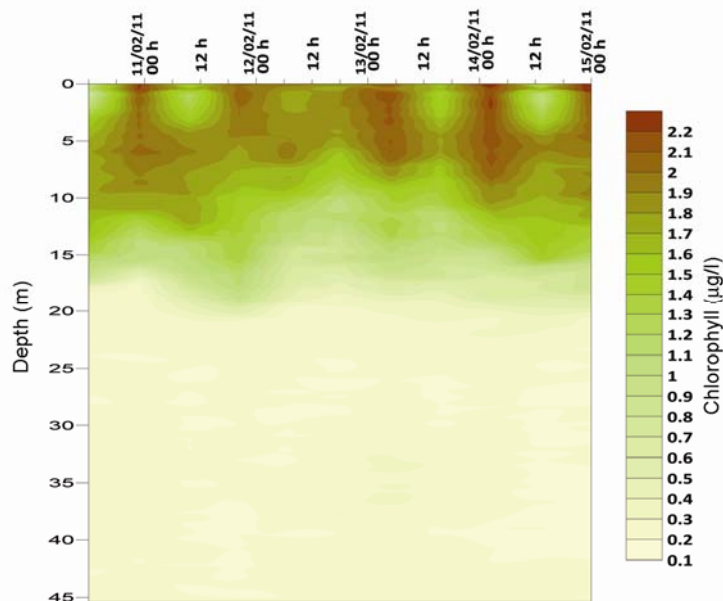
types of suspended particulates, including plankton and bacteria in the water column. The turbidity profiles (Figure 5d) show a low value of 0.5 NTU in the top 5 m layer corresponding to reasonably high chlorophyll concentration of 2  $\mu\text{g/l}$ , suggesting low amounts of non-chloro-



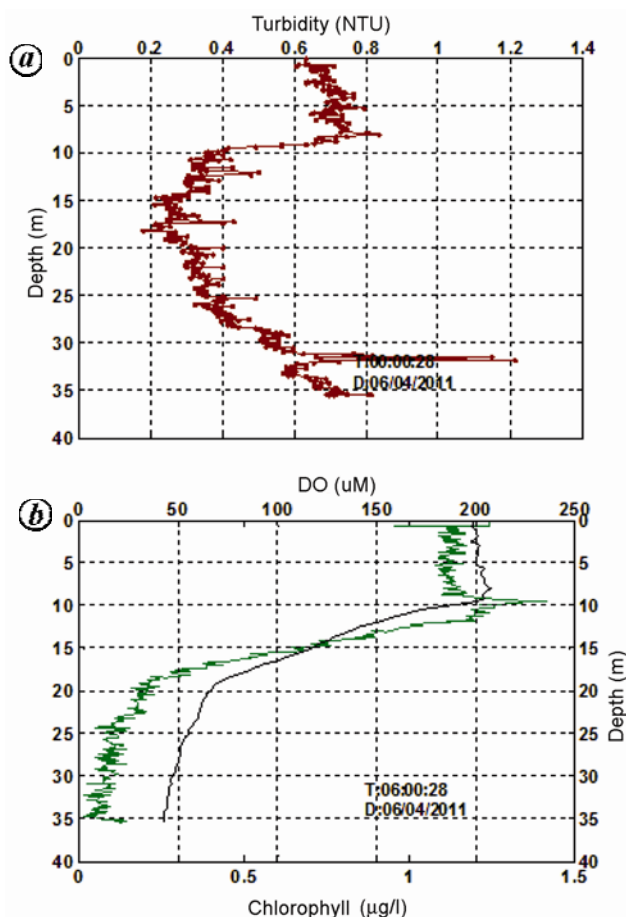
**Figure 4.** Comparison between the 1 m satellite profile (blue dots) received at NIO, Goa with the corresponding higher resolution 10 cm profile backup stored on AVP. This was a test to check the fidelity of data obtained over the satellite link.



**Figure 5.** **a**, Grouping of 19 dives of DO profiles over the period 10–15 February 2011. The constancy of shape and well-oxygenated conditions prevail during this season. **b**, Chlorophyll *a* profiles grouped during the same period. Most of the phytoplankton production occurs over the top 10 m, with mean chlorophyll concentration of  $\sim$ 2  $\mu\text{g/l}$ . **c**, Vertical structure of temperature profiles grouped over the same period. Mixed layer is shallow with low stratification. **d**, Grouped turbidity profiles for the same period. Values start increasing from 20 m downwards to the reservoir bed.



**Figure 6.** Diurnal variation of depth profiles of chlorophyll *a* fluorescence over the period 11–15 February 2011 showing the effects of photoinhibition at noon and recycled production at night.



**Figure 7.** **a**, Typical turbidity profile with depth at 6 h on 6 April 2011 during the 9-day experiment showing the anomalous mid-water low turbidity layer associated with the onset of hypoxia. **b**, Example profiles of chlorophyll (green) and DO (black) versus depth taken at 6:00 h on 6 April 2011 during the 9-day experiment associated with the onset of hypoxia. Note the steeper decline of DO and compare this with (a).

phyllous particles. This is consistent with the fact that phytoplankton are poor backscatterers known to contribute <0.2% of the total backscattering coefficient in most water bodies<sup>11</sup>. At depths beyond 20 m, the turbidity values increase to > 1.5 NTU, implying higher backscatter non-chlorophyllous contributions from bottom perturbations that stir up silt, clay, detrital particles, and particularly, submicron particles, that are known to have high backscatter coefficients.

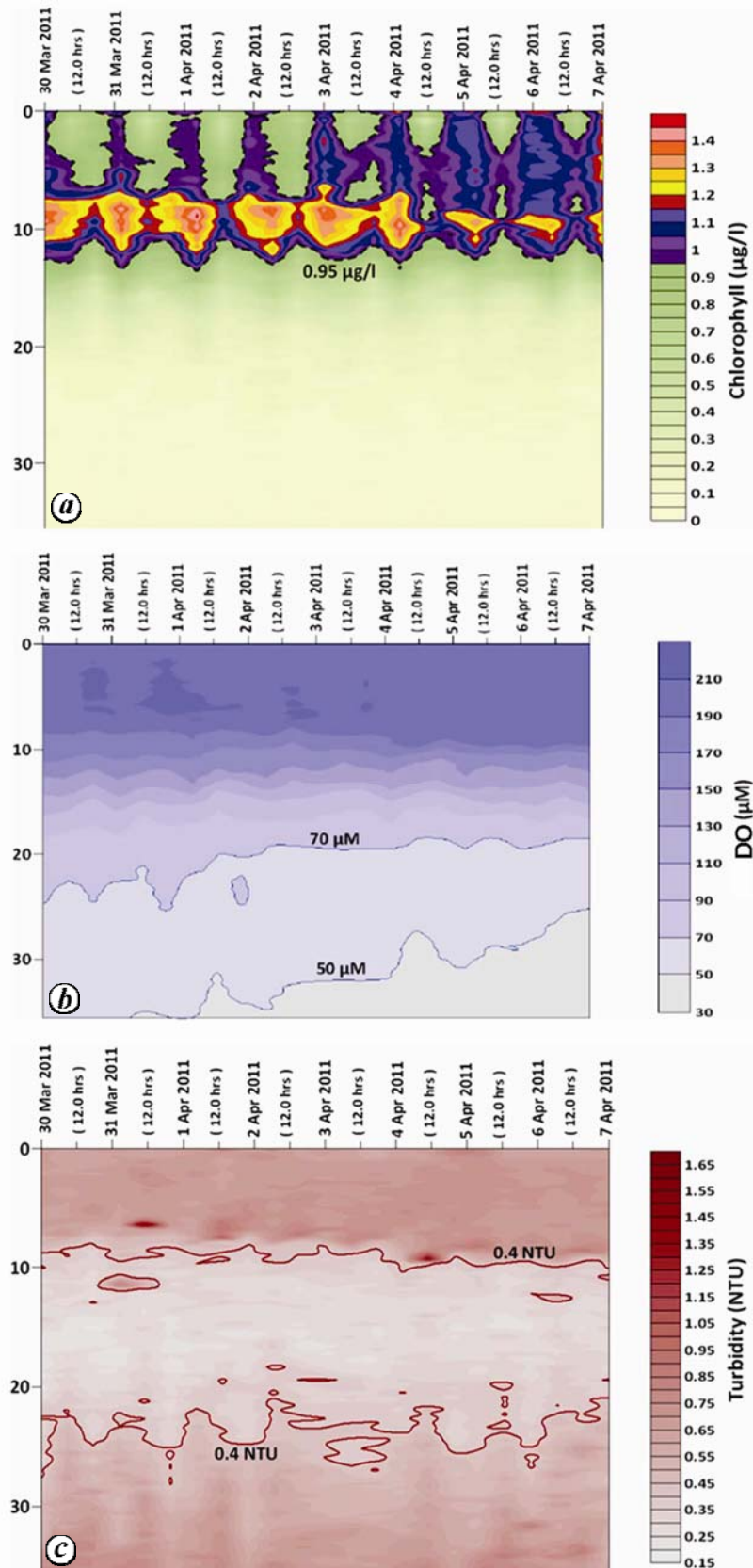
An alternative method of presenting the vertical structure chlorophyll time series profiles in Figure 5 *b* is to merge and interpolate profiles using the Surfer<sup>TM</sup> Software, as in Figure 6. Interestingly, the diurnal signals of the solar flux are now clearly visible in the vertical plane of chlorophyll *a* concentration as a function of time. There are two possible explanations that can be drawn from Figure 6.

(1) The pockets of lower chlorophyll ~ 1.4–1.6 µg/l at 12:00 h (noon) are likely due to photoinhibition of phytoplankton cells causing a decrease in the efficiency of chlorophyll *a* fluorescence. This effect is well known and penetrates down to at least 5 m in sunny tropical regimes<sup>12,13</sup>.

(2) The higher values of chlorophyll (~2.2 µg/l) at 0:00 h (midnight) are probably due to the combined effect of grazing by zooplankton and recycled primary production. The constancy in chlorophyll in the surface 10 m layer indicates that cells are well mixed, and that the rate of biomass accumulation is a function of the rate of production minus the rate of loss due to re-mineralization and sinking out of particles<sup>14,15</sup>. Since there is no upwelling process in reservoirs that would otherwise bring nutrients to the surface, the chlorophyll time series suggests that zooplankton migrating to the surface at night would feed on phytoplankton excreting nitrogen as ammonia, which replenishes the surface layers with nutrients<sup>16</sup>. As ammonia is the end-product, it is the limiting nutrient that sets the amount of recycled production in the dam. In the absence of additional measurements on nutrient concentrations, taxonomic and grazing studies with our own profiles, this conclusion remains a likely hypothesis.

*Observations of 9-day round-the-clock profiling (29 March–6 April 2011)*

Our second profiling experiment lasted for 9 days starting at 12:00 h on 29



**Figure 8.** *a*, Diurnal variations of chlorophyll are visible in this underwater time series over 9 days. Photoinhibition by phytoplankton cells can also be observed close to the surface. *b*, Time series of DO concentration profiles showing the gradual uplift of hypoxic layers from the bottom layers. The top 10 m layer in contact with the wind is well mixed and oxygenated. *c*, Mid-layer, low turbidity zone between approximately 10–20 m observed in freshwater systems that are prone to hypoxia.

March to 6 April 2011, with dives spaced (as before) at 6 h intervals. Additional battery packs were included in the hull volume of the AVP to extend the duration of monitoring by the AVP. Representative profiles of turbidity, DO and chlorophyll *a*, all taken at 6:00 h on the 6 April 2011 are shown in Figure 7. The chlorophyll maxima are now located much below the surface due to higher levels of solar radiation during these months. The DO gradient from 20 m is now steeply falling and concentrations have reached 50  $\mu\text{M}$  at the 20 m depth mark. Turbidity profiles show a minimum value in the water layer between 10 and 25 m. Temperature profiles were not measured in this experiment, but we expect that surface temperature values would increase to  $\sim 28\text{--}30^\circ\text{C}$  during the summer months.

As in the 5-day experiment before, we have merged and interpolated 28 significant dives over the 9-day profiling experiment (Figure 8). The results show further interesting effects that can only be captured in time series profiling operations:

(1) The diurnal changes are still discernable, but the maximum chlorophyll has now sunk to depths around 10 m (Figure 8*a*). Photoinhibition that was seen prominently in the February experiment, is now muted.

(2) The DO contoured time series (Figure 8*b*) shows the gradual uplift of low oxygen 50  $\mu\text{M}$  contours at 30 m, but rising to occupy shallow layers above it by 6 April. This is a strong indicator that the relatively colder hypolimnion, which remains isolated most of the year from wind mixing, with no sunlight penetration, low chlorophyll counts and higher turbidity at depth, was undergoing a transition to become hypoxic. Since the 9-day experiment ended on 6 April, we have independent confirmation that the hypoxic effect at Tillari Dam was further strengthened during April and May.

(3) The turbidity data (Figure 8*c*) are interesting as they show a clear mid water layer of lower turbidity between 10 and 20 m. A similar effect was observed

in Idukki Dam by Desa<sup>1</sup> during May in 2006 and 2007. It is highly probable that this effect is due to bacterial action promoting reducing conditions in the hypolimnion<sup>17</sup>. Further studies are needed to investigate this effect in view of the absence of a rigorous chemical analysis.

### Conclusion

This paper has demonstrated a new approach to environmental monitoring of a freshwater ecosystem in the Tillari Reservoir using high-resolution time series profiling by a patented AVP. The AVP has also been used from trawlers and research vessels in coastal waters off Goa, the Lakshadweep Islands and in shelf zone waters on the west coast of India. The profiler worked unsupervised for a maximum of 9 days transmitting vertical profiles of chlorophyll, DO, temperature and turbidity every 6 h via the satellite link to NIO located 50 km away. The satellite mode of monitoring of remote locations with unattended robot systems is trouble-free and affordable, and has a global reach. It is anticipated that the duration of monitoring can be easily extended to well over a month before a battery replacement.

The method of round-the-clock monitoring of the Tillari Dam has yielded unexpected insights into the health of the ecosystem, particularly in tracking the steady development of hypoxia, the low variability of processes that determine the diurnal changes in phytoplankton production, stratification of water layers, and the role of turbidity in the development of hypoxia.

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