

The detection of annual hypoxia in a low latitude freshwater reservoir in Kerala, India using the small AUV *Maya*

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Abstract

The Idukki Reservoir at an altitude of 748m covering an area of 53 km² is surrounded by tropical forests in the Western Ghats in the southwestern Indian state of Kerala.. We used the small AUV *Maya* with onboard sensors of dissolved oxygen, chlorophyll, turbidity, temperature and depth to monitor the water quality environment of Idukki Reservoir in May 2006. The use of AUVs in confined spaces like small lakes and reservoirs is new and uncommon requiring extra safety to be implemented. As this is a prototype AUV, we shall describe in brief key aspects of the vehicle attributes namely; its novel mechanical design, the autopilots which control the heading and cruising depth, safety and endurance of the platform. The data acquired by *Maya* revealed an acute oxygen deficiency at 21m, a mid-water low turbidity layer between 10 to 15m, and a prominent chlorophyll maximum in the thermocline region of Idukki waters at 6m. These experiments were repeated a year later in May 2007 are in agreement with the 2006 findings of hypoxia unambiguously. These are the first observations of hypoxic processes using a small AUV in any Indian lake. The relevance of these results in freshwater systems show similarities to hypoxia in saline coastal waters of the west coast of India and are discussed briefly.

Key words: *Hypoxia, dissolved oxygen, freshwater lakes, Autonomous Vehicles, eutrophication, chlorophyll, dead zones*

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Introduction

Hypoxia in aquatic systems refers to waters where the dissolved oxygen concentration is below 2 ml/L of water. A complete lack of oxygen i.e 0 ml/L is called anoxia. Since organisms that can live without oxygen (such as some microbes) are the only residents in these areas, they are sometimes called “dead zones”. Hypoxia is primarily a problem in estuaries and coastal waters, although it can also be a problem in freshwater lakes. Most organisms avoid or become physiologically stressed in low oxygen waters. (Diaz and Rosenberg, 1995). There is a clear trend of a doubling in the number of dead zones over each decade since the 1960’s (Diaz and Rosenberg 2008). Several well documented examples are dead zones that have developed in continental seas, such as the Baltic (Conley et al, 2002), Kattegat, Black Sea, Gulf of Mexico, and East China Sea, all of which are major fishery areas.

Hypoxia is often observed in a semi-enclosed water body in which thermal stratification of water layers develop seasonally, and where there exists external nutrient run offs from rivers and surrounding land formations. (Rowe et al, 2001). The development of a stratified water column is favoured by the absence of low wind and current conditions and warm surface temperatures resulting in no vertical mixing of water layers.(Chen et al. 2007, Bergondo et al. 2003). Eutrophication is a direct outcome of the rich nutrient mix that exists in the water and produces greening of the water column through the accelerated production of phytoplankton blooms .As planktonic cells die, the debris fall to the bottom where it is acted upon by microbes which require oxygen for respiration. The end product of this process is the presence of anoxic water layers close to the bed of the water body (Diaz R.,2001, Bishop et al., 2006, Diaz and Rosenberg., 2008).

This paper describes the first time observations of hypoxic processes in the freshwater environment of the Idukki Dam complex in south-western Indian state of Kerala using a small AUV *Maya* (Desa et al, 2006) developed at National Institute of Oceanography, Goa, India. An analysis of the AUV data sets validated by Dissolved Oxygen (DO) analysis on water samples at the same site, revealed the presence of acute oxygen deficiency resulting in reducing conditions in the hypolimnion which is the dark cold bottom layer of water in any thermally-stratified reservoir . These results show broad similarities to anoxic processes reported in saline coastal waters of the west coast of India (Naqvi et al. 2000, Krishnan et al. 2008).

Experimental

Mechanical aspects A simplified longitudinal section of the *Maya* AUV is shown in Figure 1. The design of *Maya* as described by Madhan et al (18) is that of a classical submarine consisting of a low drag slender ellipsoidal removable nose cone on which scientific sensors can be mounted, a main cylindrical hull of length 1.24m, wall thickness 6mm and diameter 0.234m bored out from a single solid bar of aluminum alloy and then closed at both ends by identical O-ring sealed end plates, and a tapered Myring profile tail cone enclosing a single DC motor at the extreme end for propulsion. The Doppler Velocity Log (DVL) which measures the relative speed of the vehicle is located on the main hull at a distance of 0.46m from the rear endplate. It is seated in a volume that was carved out by a transverse bore of the main hull. The three acoustic beams on the DVL radiated downwards towards the seabed. It has two stern planes and two rudders to control diving and heading maneuvers respectively. The control planes follow a standard NACA 0015 section with an aspect ratio of 4.27. Stainless steel shafts embedded in the control planes are connected to separate servomotors mounted inside the hull wall through an in-house designed temperature and pressure compensated shaft seal. The antenna stub located at the rear of the AUV accommodates a GPS (Global Positioning System) antenna, and the 2.4 GHz radio modem antenna. The modem can receive commands from the shore computer over a high-speed UHF radio link as well as transmit data over the same link.

Electronics on AUV - The electronics on board *Maya* is built around a distributed control architecture consisting of intelligent microcontroller nodes connected to each other through a Controller Area Network (CAN). The CAN nodes are assigned low level tasks that control fin and rudder movements, motor thrust, manage power usage and trigger safety operations. The main node is a PC/104 stack consisting of an Intel 486 compatible CPU card, a dual port CAN card and a four port serial card. A specially created embedded Linux is used as the Operating System (OS) for the main node which runs on the on-board flash disk (the Disk On Chip–DOC) and uses a 128 MB compact flash disk for data storage. High performance tasks are assigned to the main node which include data acquisition from the Attitude and Heading Reference System (AHRS) which provides roll, pitch, yaw, the corresponding rates, and the heading reference, GPS, DVL, mission guidance, control, navigation, and radio modem communications with the shore computer. The science node acquires data from sensors on the nose cone, and receives position and time stamps from the main node. See Table 1 for the main specifications of *Maya* AUV, and Figure 2 for a full length photograph of the AUV in water with nose cones, four control foils, and propulsion motor.

Science sensors on Nose Cones of AUV - The semi-elliptical nose cone is free flooding and mounted on an aluminium collar that is threaded onto the main hull. The cone covers the front end plate held down by a threaded retainer ring ; removal of the ring and endplate provides access to the internal parts (batteries, electronics, and gyros) resident within the main hull. The volume within the cone can be used to accommodate wet sensors that are wired to power and signal connectors mounted on the front end plate. Similarly, removal of the rear end plate permits access to the servomotors, electronics, shaft seals, and communications module.

The choice and type of scientific sensors on *Maya* was decided early in the development by the oceanographic problems we had in mind for the first field tests. The limited volume offered by its nosecone constrained the choice of sensors by size, weight, and power, and made it necessary to fabricate different nose cones with mission specific sensors. For example, physical properties of the ocean are best studied with a Conductivity-Temperature-Depth (CTD) sensor customized to fit within the available volume offered by the nose. Other missions on biogeochemistry require a combination of Dissolved Oxygen (DO), Chlorophyll, and turbidity sensors fitted on an identical nose cone. Photographs of the nose cones used in the Idukki studies are shown in Figure 4 . The thermistor on the customized CTD module and the DO sensor have response times less than 3s and 25s respectively, longer than the faster chlorophyll cum turbidity (~ 125ms) and conductivity(~95ms) sensors (see Table 2). The DO sensor has some useful advantages namely its pressure behaviour is fully reversible, it consumes no oxygen, the optical paths are all internal to the sensor, and its long response time suggests its suitability to slow profiling (Kortzinger et al. 2005). As we shall see later, response times of sensors need to be considered when deciding the dive pattern of the AUV as this affects the shape of the downcast and upcast profiles significantly.

Autopilots for Heading and Diving Maneuvers - The depth and heading control systems of *Maya* were designed using the LQ (Linear-Quadratic) optimization technique that was based on a mathematical model of the AUV obtained by resorting to Analytical and Semi-Empirical (ASE) methods (Barros et al.2008). For simplicity, the model assumes two non-interacting systems for the vertical and horizontal planes linearized about a nominal speed of 1.2 m/s to predict the hydrodynamic derivatives for the submerged vehicle. The model outputs simulate its maneuverability characteristics given only inputs from common mode deflection of the stern and rudder control planes. This inexpensive approach to model development avoids the use of tank tests and Planar Motion Mechanism (PMM) devices to estimate the hydrodynamic derivatives.

The controllers have met the requirement of performance and stability in both the vertical and horizontal planes and this was investigated by Maurya et al (19). At a practical level, the use of the delta implementation removes the bias from the stern planes obviating the need of a special sensor for precision measurement of control plane angles (Kaminer et al 1995). Extensive tests of the autopilots were first carried out at the *Amthane Reservoir* in Goa, India so as to arrive at the best set of gains and bandwidths. In order to assess, the accuracy of depth control of *Maya*, a short staircase test of the vehicle to controlled depths of 1.5m and 2.5m was conducted at the reservoir. The depth controller drives the error signal i.e the difference between the set reference depth and the current depth sensor measurement until it is close to zero. In practice it was possible to control depth to within $\pm 5\text{cm}$ in calm conditions of the dam. This small error can arise from inherent noise and external disturbances to the sensor. In this sense, the controller output is independent of the accuracy of the pressure sensor. The Honeywell PPTR pressure sensor was calibrated using a standard oil pressure gauge at constant room temperature and was checked to be within the stated accuracy of 0.05% of full scale 500 psia i.e approximately 17cm. The simulated response from the control system toolbox of MatlabTM using the model in the vertical plane is shown for in Figure 5. The tests have proved useful when *Maya* was deployed in real conditions at sea with little or no changes in control gains.

Navigation Technique on AUV - Navigation on an AUV is important as it provides an estimate of the present position of the vehicle. When the *Maya* AUV is on the surface, GPS is used to obtain position as Latitude and Longitude in degrees converted to Universal Transverse Mercator (UTM) inertial coordinate system and accurate to within $\pm 5\text{m}$ RMS. As there are no GPS signals available below the sea surface, underwater position (X,Y) estimation of the AUV was achieved by standard dead reckoning methods that involve the integration of the DVL velocities in an inertial frame of reference. The underwater Z coordinate is not estimated but set equal to the pressure transducer output in meters. Simple Line of Sight (LOS) way point guidance scheme with path following was used in the guidance of the craft. The switch from using the GPS to DVL and vice versa is done smoothly using a complimentary filter. A path following guidance test at Supa Dam, Karnatka, India was conducted with *Maya* AUV performed a square mission on the surface and two consecutive depths of 3m and 5m. (see Figure 6)

Safety Aspects on AUV - Incorporating safety features on the AUV is of prime importance and we have considered and implemented the following:

- Power safety which monitors the bus voltage on a network node, and redirects the AUV to home coordinates if the power level falls below a minimum threshold level.

- Software safety ensures that the DC thruster is shutdown if the vehicle crosses programmed depth, or exceeds a set pitch angle.
- Built-in software timeouts ensure that the AUV surfaces if it takes more than the estimated mission duration.
- Safe recovery of the vehicle was done by incorporating a small positive buoyancy so that it can re-surface in the event of a system failure. The total weight of the *Maya* AUV with all attachments averages to $W = 54.7$ kgf. The intrinsic buoyancy from the hull and nose cone is about 43.4 kgf; insufficient to make the AUV float. Therefore, the bare hull was clad in a PVC foam jacket such that a net buoyancy between 0.5 to 1 kgf was achieved.

The *Maya* AUV differs from other commercially available small AUVS namely Remus (USA), and Gavia (Iceland) in several important aspects namely (a) a high degree of modularity in mechanical design with quick turnaround times (~30 mins) of deployment and retrieval in the field (b) distributed electronic architecture and modular software expandability (c) control algorithms based on the LQR technique provide high accuracy and stability in commanded depth (± 5 cms) and heading ($\pm 2^\circ$), and removes the offsets on control plane positions (d) the development of a vehicle model for *Maya* was based on ASE techniques that eliminate the need and the cost of expensive tow tank tests to determine hydrodynamic derivatives of the vehicle (e) New sensors are easily incorporated on the science node without affecting the underlying software structure (f) ease of trimming of the vehicle's buoyancy (g) practical safety features that enable it to be recovered in case of failure at sea.

Field Experiments at the Idukki Reservoir

Site. The Idukki Reservoir at an altitude of 748m is surrounded by tropical forests in the Western Ghats in the southwestern Indian state of Kerala. It is formed by three dams; Idukki arch dam (171m high), Cherutoni (136m high) and Kulamavu (100m high). The reservoir covers an area of 53 km², and receives an average rainfall that varies between 444 cm to 508 cm. It was chosen as the site to test the depth control of the AUV in deeper waters and also to use the AUV to collect scientific data in a freshwater body which at most times, is unaffected by perturbations from wind waves and currents. Two sets of field trials over the period 7th to 12th May 2006 and again from 20th to 27th May 2007 were conducted at a location called Vairamani (Lat. 9° 47'14''N, Long. 76° 55'58''E) shown on the map in Figure 3. The presence of tree stumps on the surrounding hills at higher levels provides a measure of the large scale deforestation that was needed to create the Idukki Reservoir. The slumping of valleys encompassing the reservoir can result in the degradation of slopes, rain water wash, siltation of the

reservoir from the accumulation of sediments, and degradation in forest cover are documented by Sassendran et al. 1984 in (23). This can also affect the chemistry of the reservoir waters especially with regard to the oxygen levels in the water.

Staircase dives of the *Maya* AUV at the Idukki Reservoir. The AUV was first commanded to execute a series of successive staircase dives to progressively larger depths starting with a dive to 2m, and ending at 21m (see Figure 7). The descent staircase was designed with 6 levels and took 120s to level out at the 21 meter depth layer. In contrast, the ascent from 21m to the surface took only 75s. The dive rates between levels was typically ~ 0.3 faster than the dive rate of 0.08m/s of a standard APEX float (15). The total time taken spent underwater for the 21m dive was 220s, and the horizontal distance traveled in that time was ~ 400 m. The duration of a step level was set to 20s response time of the DO sensor, and then to accommodate as many steps as is possible from the surface to the maximum depth of the mission. This approach takes care of all other sensors with response times less than the maximum. When the AUV reaches a step, it cruises horizontally at this depth at a constant speed ~ 1.0 m/s for the duration of the step, before diving down to the next deeper level. The staircases were deliberately chosen to be asymmetric, so as to collect sensor data during descent dives only, and to save time and power while ascending at a faster rate. We have preferred to base our observations on data from descending staircases only.

Accuracy of the Dissolved Oxygen Sensor. Soon after receiving the factory calibrated Dissolved Oxygen (DO) sensor, we made simple pre-calibration checks on it by mounting it on the tip of the nose cone and logging dissolved oxygen concentrations from straight line surface runs of the AUV at the freshwater *Amthane Dam*, in Goa, India. Surface water samples were collected at the site behind the tracks of the AUV, and analyzed in the laboratory by the standard Winkler titration technique. It was observed that the DO sensor underestimates the laboratory method by $< 6\%$, but within the claimed accuracy of the sensor.

Results

Vertical profiles of sensor outputs were extracted from staircase dives (2m to 21m) with the nose cones carrying a (DO) and chlorophyll cum turbidity sensor and a CTD of Figure 4. All sensors were sampled at 1Hz, each data sample was position, time, and depth stamped and stored together on flash memories of the science node controller electronics. The data presented here is combined from the two studies made in 2006 and 2007 at the same site on the Idduki Reservoir.

Temperature profiles. The 2D downcast temperature profiles extracted from the CTD sensor are shown plotted in Figure 8 during May in 2006 and May 2007. Both profiles show a shallow mixed layer with the temperature of 29.5 °C in the top 2m, and sharp drop there after from 28 °C. Despite the altitude of the Idukki Reservoir (748m), the presence of strongly stratified water in a freshwater body located at such low latitude is unusual. This stratification has an important impact on the distribution of chemical and biological properties as summarized below.

Chlorophyll profiles. The chlorophyll profiles in Figure 9 reveal a pronounced sub-surface maximum between 5m to 10m with a peak concentration of 2.75 µg/L at ~ 6m for both years 2006 and 2007. This probably arises from the inhibition of primary productivity by high irradiance at the surface such that maximal photosynthesis occurs deeper in the water column. The chlorophyll concentration decreases rapidly thereafter to ~0.25 µg/L below 15m.

Dissolved Oxygen (DO) from downcast and upcast profiles. The DO profile in Figure 10 was assembled using data from successive profiles of the descent dives to 2m, 5m, 10m, 15m, 21m. It shows high values of 224 µmol/L in the top 5m layer decreasing very rapidly with a gradient ~ 20 µmol/L per meter to ~ 6 µmol/L at 21m. The high values of DO near the surface are caused by a combination of the exchange of oxygen between the atmosphere and the epilimnion (the top-most layer in a thermally stratified lake) and the release of oxygen due to photosynthesis from algal cells in the upper layer. The weak subsurface DO maximum is probably related to the above-mentioned subsurface chlorophyll maximum. The decrease in DO concentration below the epilimnion should be due to respiration of organic matter sinking from the euphotic zone (the depth of the water in a lake or ocean that is exposed to sufficient sunlight for photosynthesis to occur). For the sake of completeness, the DO profile from the ascending 21m staircase is also shown plotted in Figure 11. This clearly shows that fast ascent rates (~ 0.3m/s) of the AUV can give spurious results if response time (~ 25s) of the slow DO sensor is not considered in the design of the staircase mission.

DO profiles from successive seasons - The DO profiles taken with the AUV at the same site of the Idukki Reservoir on 12th May 2006 and 20th May 2007 is compared in Figure 10. There is a remarkable similarity in the profiles indicating that the hypoxic effect is real and seasonal. Independent analysis of DO values from water samples at different depth during both trips are also drawn into Figure 10. The higher surface DO values of 250 µmol/L are consistent with windier conditions in the late evening of 20th May 2007. The water sample set shows the first indication of anoxia below 20m depth layer reaching values as low as 9 µmol/L at 21m, and confirms what was detected independently through AUV dives.

Several independent laboratory based water sample measurements at other neighbouring sites to the Vairamani site showed that the hypoxia is widespread in the vast Idukki Reservoir Complex.

Turbidity profiles - Turbidity gives a measure of the light scattered by particles in suspension and is expressed in Nephelometric Turbidity Unit (NTU) units. The turbidity profiles in Figure 12 shows data measured during successive seasons in the summer months of 2006 and 2007. There is clear evidence of a turbid surface layer in the top 5m, followed by a clear zone between 10m to 15m, and then an increasing turbidity signal with depth that traces the progressive decrease in DO from hypoxic ($> 4.4 \mu\text{mol/L}$) to suboxic levels ($<4.4 \mu\text{mol/L}$) beyond 21m.

Horizontal sampling of dissolved oxygen by the AUV.

Besides the capability of vertical sampling as shown above, AUVS can be used to sample in the horizontal plane i.e. collect data as it moves along tracks on horizontal planes at different depths below the sea surface or at the surface. Further, by independent control of the stern and rudder planes, it can also be made to execute corkscrew maneuvers in the 3D volume of any water body that would enable it to do vertical and horizontal sampling simultaneously. The *Maya* AUV was programmed to execute several long missions fitted with DO, Chlorophyll and CTD sensors. In one such mission it was made to complete several line transects of length 560m running below the surface at a depth of 1.2m with a surface pop-up at midway point along the track and several turnarounds at the end of the transect. The total distance covered was ~ 3.5 kms in a continuous run of 48 minutes. The results of this experiment are shown in Figure 13 where *Maya* samples DO properties as it yoyo's between the surface and a depth 1.2m. The colors on this track show that it has been able to capture the small changes in the weak DO maximum shown in the vertical profiles of Figure 10 and 11.

Discussion

Idukki reservoir has several features which makes it an excellent site to investigate biogeochemical processes. First, Idukki dam has been built across the river Periyar, one of the few perennial rivers in Kerala having high biologically productivity. It exhibits a well-documented seasonal cycle of phytoplankton production (C.M.Joy et al, 1990). Second, the deep basinal water becomes anoxic during the summer due to the coupling of high biological productivity, chemical processes and thermal stratification. To the best of our knowledge, the presence of acute oxygen deficiency at depth in the Idukki freshwater system has not been reported earlier.

Seasonal oxygen-deficiency has been known to develop in freshwater bodies as a result of the summertime stratification which isolates the winter water from the surface layer (the epilimnion) such that DO below the thermocline (the hypolimnion) reaches anaerobic levels (Nurnberg et al, 2004, Bellanger et al, 2004, Valle-Levinson et al, 1995). For instance, observations in Lake Kizaki in Central Japan by Yoh et al showed an acute oxygen depletion ($DO < 4.46 \mu\text{mol/L}$) in the hypolimnion (Yoh et al, 1983). This led to denitrification and the accumulation of nitrous oxide in bottom layers. Similar denitrifying processes were recorded by the same authors in the shallower Lake Fukami-ike (8.5m depth). A common feature seen in both freshwater bodies was the presence of stratification of the water column with temperatures $\sim 17^\circ \text{C}$ in the epilimnion and $< 10^\circ \text{C}$ in the hypolimnion. However, unlike the Idukki Reservoir, Lake Kizaki is at high latitude and a higher altitude and so the observed reducing conditions in Idukki waters is highly unexpected (Helly et al, 2004)

The Nepheloid Layer of Idukki Reservoir

Optical transparency within the oxygen deficient zones of the eastern tropical Pacific Ocean show prominent turbid layers that are caused by the presence of suspended particulate matter as detailed by Garfield et al. 1983 and Spinrad et al. 1989 (see 11,24 respectively) . The maxima in the beam attenuation profiles were found to correlate strongly with the secondary nitrite maxima (SNM), and with bacterial abundance maxima. Later optical beam attenuation and biochemical measurements by Naqvi and co-authors in 2000 (20) in the Oxygen Minimum Zone of the Arabian Sea also revealed a strong coupling between the vertical distributions of mid-depth Intermediate Nepheloid Layer (INL) and the SNM. Further evidence gathered by these authors from correlations with profiles of particulate protein, and bacterial abundance at the same locations suggested that biodegradable bacterial biomass might account solely for the INL associated with denitrification.

The turbidity profile of Figure 12 was plotted from signal accessed concurrently with the chlorophyll values from the fluorometric payload as the AUV executed staircase dives. The higher surface turbidity in the top 5m layer can be understood to result from backscattering of the optical signal at 700nm from detritus or suspended algal cells, or even from a polydispersion of heterotrophic bacterial cells present near the subsurface chlorophyll maximum. The turbidity decreases significantly from 5m to 15m reaching a minimum, and then shows a trend towards high values from 15m to 20m beyond which there are no data as the dive was terminated. It seems very probable that the increased turbidity is related to the prevalence of reducing conditions in the hypolimnion. The alternative possibility of the high turbidity at 20m and beyond as being the result of bottom re-suspension of sediments can be ruled out as the measurement site had a depth of 40m.

The data presented here using the *Maya* AUV suggest strong parallels with what happens in the oxygen minimum zone of the Arabian Sea (Naqvi et al 2000). In the Idukki Reservoir, it is likely that a subsurface plankton bloom (see Figure 9) supplied a high flux of organic matter that triggered suboxic conditions near and below 20m. The presence of soil erosion and deforestation in the hills surrounding the reservoir may be contributing to a continuing supply of nutrient load that favours conditions for the initiation of subsurface plankton blooms. The absence of external perturbations of currents, waves, advection, and transport of matter makes the Idukki Reservoir an ideal closed system in which to study processes that are caused by severe oxygen depletion accompanied by the formation of turbid layers.

Summary

The AUV technology reported here has demonstrated through the technique of staircase dives that (a) high resolution vertical profiles from on board sensors of DO, Chlorophyll, turbidity, temperature can be obtained in a short time frame with the advantage of repeatability of measurements and (b) that small AUVs can be used in confined spaces without the need of sophisticated navigation that is required at sea. The data collected by *Maya* AUV shows that seasonal hypoxia develops annually in the Idukki Reservoir during the summer months when the water is warm and strongly stratified. Nutrient run-off from the slopes of the surrounding hills of the Western Ghats coupled with the above conditions results in eutrophication from phytoplankton blooms below the water surface. The consequence of this process is the appearance of oxygen consuming bacterial layers that feed on the falling flux of dead phytoplankton cells. The chain of events result in the formation of hypoxic layers at depths typically greater than ~15m. The effect will be diminished in the monsoon months (June to September) when winds and rain will break-up stratified layers. The measurements reported here pose important questions for climate change scenarios of the future e.g. –

1. The existence of hypoxia in waters of Idukki Reservoir may lead to the probable accumulation of nitrous oxide (N₂O) a greenhouse gas: a by-product of the denitrification process (see Yoh. et al. 1983) observed frequently in hypoxic zones.
2. Idukki Reservoir was constructed by the deforestation of hill slopes in the Western Ghats. The ecosystem response to this anthropogenic interference has led to seasonal hypoxia in the summer months. Can the hypoxic effects observed here also occur in similarly constructed landlocked fresh water reservoirs of the world ? This needs to be investigated at other similar sites.
3. The results presented here provides scope for the use of molecular bar-coding techniques that could help distinguish genetic differences, and similarities between freshwater bacterial flora and their

marine counterparts, both of which appear to be playing similar roles in denitrifying processes on land and in the ocean.

Apart from its use in freshwater reservoirs, rivers and lakes, the small AUV Maya was deployed in the coastal waters of the Arabian Sea to a depth of 40m to collect CTD profiles (Desa et al 2007) . Studies planned for this year with Maya will be to advocate the use of AUVS as a working tool for ocean scientists. For this purpose, detailed investigations will be carried out with biogeochemists to document the spatial and vertical extent of anoxic processes and underwater algal blooms that are observed on the west coast of India after the monsoons (Naqvi et al 2000). The endurance time of Maya is approximately 7 hrs enabling spatial data along 25 km long near shore transects perpendicular to the coast in areas where anoxic zones are present.

There has been a surge of interest by several groups in Europe and the USA (Ghabcheloo et al 2005) on the control and coordination of multiple autonomous platforms that could include autonomous surface vehicles (ASV) , gliders, and propelled AUVS. This would require robust methods of navigation that employ fault tolerant recoverable acoustic links between moving vehicles. Special environmental sensors (light, magnetic field) and long life power sources would also be needed to extend the duration of AUVS to navigate autonomously underwater for long periods with minimal resurfacing to correct vehicle coordinates.

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Table I: Main specifications of the *Maya* AUV

<i>Vehicle Specifications</i>	
Al Alloy Hull Dimensions	L = 1.742 m ; Diameter = 0.234m
Weight in air	~54.7 kgf
Nose and Rear Cones	FRPG/Acetal (Removable)
Tested Depth	200 m
Propulsion	DC brushless motor
Nominal speed	1.5 m/s
Endurance	~ 7.2 hrs (propulsion); 11.5 hrs (payloads)
Power source	Lithium Ion Polymer cells (24V/18Ah- payloads; 100V/9Ah- thrusters)
Total average power	130W (includes thrusters & payloads)
Electronics	Distributed networked nodes (Main node-Linux DOC on PC104 & low level CAN nodes)
RF Communications	2.4 GHz, 115kbaud
<i>Vehicle Payloads</i>	Doppler Velocity Log Attitude & Heading Reference System Pressure sensor, GPS

Table 2. Scientific sensors used on *Maya* AUV

Sensor	Response Time	Range & Accuracy	Sampling	Weight (gms)	Power	Manufacturer
Dissolved Oxygen	< 25s (< 6s without protection layer)	0-500 $\mu\text{mol.L}^{-1}$. (<8 $\mu\text{mol.L}^{-1}$ or 5%)	1s - 24 hrs	120 gms	960 mW	Aanderaa, Norway Model 3835
Chlorophyll	< 125ms	0.02–60 $\mu\text{g/l}$	to 8Hz	80 gms	960 mW	WetLabs USA FLNTUS 396
Turbidity		0–25 NTU				
Conductivity (Inductive)	< 95ms	0 - 70 mS/cm ($\pm .003\text{mS/cm}$)	to 6Hz	389 gms	120 mW	RBR, Canada Customised standard Model XR-420 CTD
Temperature (Thermistor)	< 3s	-5 °C to 35 °C (± 0.002 °C)				
Pressure (depth)	Instant	0 to 740 dBars ($<0.001\%$ FS)				