Real-time Monitoring of African Aquatic Resources using Remote Sensing

With Special Reference to Lake Malawi

NRI NATURAL RESOURCES INSTITUTE
Overseas Development Administration

Aquatic resources often play a vital role in the lives of local populations and national economies. However, in Africa the lack of immediate information on changes in these resources frequently hinders their effective management. The use of remote sensing satellites for the simultaneous recording and reporting of events permits the collection of real-time information that can be acted upon immediately.

Real-time Monitoring of African Aquatic Resources using Remote Sensing describes work carried out on Lake Malawi. Daily, remotely sensed maps of lake surface temperature were compared with information collected *in situ*. Fisheries scientists found strong agreement between the two methods and were successfully able to monitor changes in the structure of local fish populations following changes in lake water temperatures.

This booklet will be of interest not only to fisheries managers but to all those concerned with the study and management of African lakes, reservoirs and wetlands as the possibilities expand for monitoring environmental changes using remote sensing.

Real-time Monitoring of African Aquatic Resources using Remote Sensing

With Special Reference to Lake Malawi

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NATURAL RESOURCES INSTITUTE
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The Natural Resources Institute (NRI) is an internationally recognized centre of expertise on the natural resources sector in developing countries. It forms an integral part of the British Government's overseas aid programme. Its principal aim is to alleviate poverty and hardship in developing countries by increasing the productivity of their renewable natural resources. NRI's main fields of expertise are resource assessment and farming systems, integrated pest management, food sciences and crop utilization.

NRI carries out research and surveys; develops pilot-scale plant, machinery and processes; identifies, prepares, manages and executes projects; provides advice and training; and publishes scientific and development material.

Cover picture shows Malawian fishermen hand-hauling a beach seine net at Senga Bay, Lake Malawi. Photograph taken by J. Barraclough.

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Introduction

This publication is aimed at scientists and decision-makers concerned with the study and management of African aquatic resources. It should assist such professionals when they are considering, firstly, the potential of real-time remote sensing as an aid to investigating the temporal and spatial structure of aquatic ecosystems, and secondly, the use of the acquired data in the management of aquatic resources and fisheries. It comes at a time when the World Bank has identified Africa's three largest lakes, Victoria, Tanganyika and Malawi, as sites requiring special study, particularly in view of the high diversity of their indigenous fish fauna. Study of these lakes falls under the World Bank's Global Environment Facility (GEF) group of projects instigated after the 1992 Rio de Janeiro Earth Summit.

The main text of the booklet describes the potential of real-time remote sensing in the study and management of African aquatic resources. Technical information has been placed within boxes throughout the text and a glossary of terms is provided on page 21. Lake Malawi is used as an example. This is where a British Overseas Development Administration (ODA) sponsored Natural Resources Institute (NRI) project was instigated to provide daily maps of lake surface temperature to assist a concurrent fish resources assessment programme. This fell within the brief of the Local Applications of Remote Sensing Techniques (LARST) group of the NRI. Remotely sensed temperature maps were obtained using locally captured data transmitted from the National Oceanic and Atmospheric Administration (NOAA) series of satellites during the period 1992 to 1994. *In situ* temperature data collected by the ODA fisheries programme (the United Kingdom/Southern African Development Community Pelagic Fish Resources Assessment Programme; see Menz, 1995; Wooster *et al*., 1994) allowed for the direct calibration of the remotely sensed temperatures via a comparison between the satellite-derived data and conditions observed *in situ*. Fisheries scientists were able to make an assessment of the usefulness of the satellite images of lake surface temperature to describe limnological events and how these data may be interpreted from the point of view of fisheries management. Further consideration is given to wider applications of remote sensing in the study of the aquatic resources of the continent.

Importance of aquatic resources in Africa

In the more arid parts of tropical Africa water is frequently a limiting factor to agriculture. Therefore, the study of aquatic systems is of great economic importance. In areas where surface water is more abundant, it forms an important natural resource in the form of lakes, rivers, reservoirs and temporary water bodies (floodplains and marshes). The most obvious direct economic use of water bodies is in fisheries, although knowledge of the nature and extent of surface water also has major implications for the management of other areas of the economy. These include irrigation, hydroelectricity, pollution monitoring, navigation and conservation.

Fish form a critical source of animal protein in the developing world and the proportion of fish protein in human diets is often notably high. Of the forty countries ranked highest by the percentage of fish protein in their total animal protein diet, only Japan is not a developing country.

Worldwide there are more than 100 million people who are directly dependent on the fishing industry for their livelihood. According to the Food and Agriculture Organisation of the United Nations the total annual world production of fish is around 100 million tonnes. Of this figure some 13 million tonnes are produced by aquaculture, while the remainder depends on the exploitation of naturally occurring fish populations. Fisheries remain the last major hunter-gatherer occupation, and management of a sustainable fishery relies heavily on a knowledge of the processes occurring in the aquatic ecosystem.

Satellite remote sensing of aquatic ecosystems

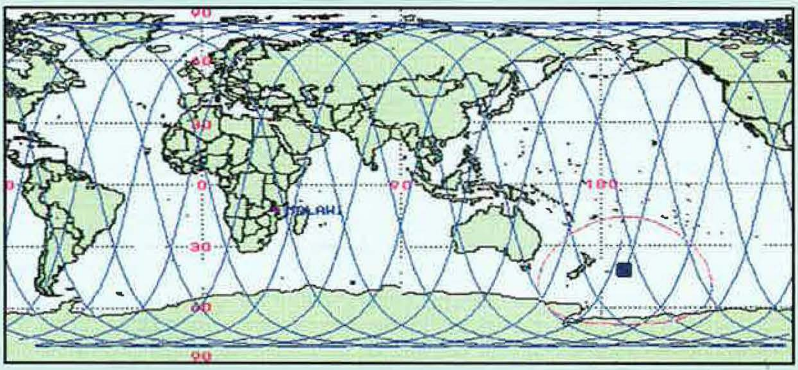
Aquatic systems are dynamic and significant changes can often occur over a period of a few days. Therefore, if information is to be obtained from remote sensing satellites and is then to be acted upon, there is a requirement for what is termed real-time information. This can be defined as the simultaneous recording and reporting of events. For remote sensing this is dependent on an on-site satellite data reception and processing capability. Additionally, for such information to be an effective management tool, it needs to be processed to a level that can easily be understood by non-remote sensing specialists. This generally involves the production of maps or images showing variations of the appropriate parameter (e.g. water surface temperature) either colour-scaled or contoured.

The principal advantage of remotely sensed data is that large areas can be sampled instantaneously and at frequent intervals. In addition the satellite-derived data are relatively cheap and offer the potential for obtaining long time series at low cost. This allows consideration of long-term or inter-annual variations of aquatic systems which would be particularly useful in the African situation where data of this kind are notably absent.

The frequency of imaging of any part of the Earth's surface by a satellite depends on both its orbital characteristics and on the width of the swath imaged below the satellite. There is a general trade-off between the swath width and the resolving power of the sensor (the size of each picture element in the data) such that a high resolution sensor (for example, 30 m picture elements) will have a relatively low swath width and will thus only image the same point on the Earth's surface relatively infrequently (for example, every 16 days). If quantitative information is required from the remotely sensed data, corrections need to be made to allow for the effects of variable transparency of the atmosphere between the Earth's surface and the satellite sensor. This usually involves the development of mathematical functions which enable a factor to be derived that provides compensation for variable atmospheric effects. The main orbital characteristics of the NOAA series of satellites are given in Box 1. Details of the sensors carried on board the NOAA satellites and the derivation of correction factors are outlined in Box 2. The data transmitted from NOAA satellites are not encrypted and are therefore free to be collected, processed and disseminated by any suitably equipped receiving station.

Box 1—Orbit characteristics of the NOAA sites of satellites

The orbit track of NOAA satellites is north–south at an angle of 102° to the equator and at an altitude of around 850 km. The orbit is sun-synchronous and passes each point twice a day at approximately the same time of day. There are currently three operational NOAA satellites but with the recent failures of NOAAs 11 and 13 there is no midday/night-time NOAA satellite. The next NOAA satellite is, however, due to be launched at the end of 1994 and will have a midday/night-time pass. Full coverage of the Earth's surface is possible twice a day from each satellite but in reality it is less useful to collect images where the viewing angle is greater than 50° and therefore the number of useful passes is somewhat reduced. At subsequent 24-h periods the NOAA angle of elevation between the in-range satellite and the point of interest on the Earth's surface varies. This allows approximately 8–10 useful images per week for any Earth location, for a single NOAA satellite and an image resolution of 1.1 km directly below the satellite. The low orbit of the NOAA satellites means that any receiving station must track the satellite as it passes in order to receive the transmitted stream of data. The area delineated around the satellite on the figure below is the reception area of the satellite. Any receiving station within the reception area can obtain information and therefore image the Earth's surface immediately below the satellite.



Typical orbit track of a NOAA satellite in a single 24-h period. The satellite position is shown, in this case, overhead east of New Zealand.

Box 2—Details of the sensor carried on the NOAA series of satellites

The imaging sensor carried on board the NOAA satellite series is known as the Advanced Very High Resolution Radiometer (AVHRR). The AVHRR operates in five distinct wavebands, the characteristics of which are given in the first table below. The AVHRR sensor was originally designed to assess meteorological conditions but it was quickly realized that it could also be used to measure a number of other environmental parameters. A list of these parameters regarded as useful in the description of aquatic systems is given in the second table below.

Details of the AVHRR carried onboard NOAA satellites.

AVHRR channel	Wavelengths
1	0.58–0.68 μm (green-red)
2	0.72–1.10 μm (near infrared)
3	3.55–3.93 μm (mid infrared)
4	10.50–11.50 μm (thermal infrared)
5	11.50–12.50 μm (thermal infrared)

Main parameters measurable using the AVHRR that are useful in describing aquatic systems.

Parameter measured	AVHRR channels used
Ice cover	Channels 1 to 5
Vegetation/chlorophyll	Channels 1 and 2
Suspended sediment	Channels 1 and 2
Land/water boundaries	Channels 2, 4 and 5
Water surface temperature	Channels 3, 4 and 5

An initial study was conducted to investigate the applicability of certain atmospheric correction methods to the problem of remotely estimating tropical lake surface temperature from AVHRR data.

This study included an analysis of the degree of error that would be expected in such temperature estimates. Initial calculations of water surface temperature used a previously published algorithm incorporating data from AVHRR channels 3, 4 and 5. This algorithm was then fine-tuned for Lake Malawi using actual night-time water surface temperatures collected simultaneously from onboard the lake fisheries project research vessel. Using this modified algorithm satellite-derived temperature estimates were found to be accurate to within 0.7°C for Lake Malawi. Details of the derivation of this algorithm are outlined in Wooster M., Sear, C., Patterson, G. and Haigh, J. (1994) Tropical lake surface temperature from locally received NOAA-11 AVHRR data—comparison with *in situ* methods. *International Journal of Remote Sensing* **15:** 183-189.

Lake Malawi—physical structure and biology

Lake Malawi (often referred to as Lake Niassa) lies in southern/central Africa between 9° 30' S and 14° 30' S (Figure 1). It is located in the western arm of the East African Rift Valley and is the southernmost of the large African Rift lakes. The lake is long and narrow with an approximate length of 550 km and a mean width of 50 to 60 km. With a surface area of 28 800 km^2 and an average depth of 292 m (maximum depth of 704 m) the lake is one of the largest in the world. Lake Malawi is the second largest lake in Africa by volume, after Lake Tanganyika which lies north of Lake Malawi in the same arm of the East African Rift Valley. The volume of Lake Malawi is 8400 km^3 and this represents almost 7% of the total amount of freshwater contained in all the lakes, ponds and rivers of the world.

Although the total fish catch from Lake Malawi is not remarkably high (for example, the annual total for 1986 was 51 000 tonnes), it represents an important component of the diet of the local population. Lake fish con-

Figure 1—Location of Lake Malawi in southern/central Africa.

tribute half the dietary input of high-quality animal protein for Malawi's population of 8 million people.

As is common with many of the deeper tropical lakes, the water in Lake Malawi is permanently vertically stratified. This condition is known to lake scientists as meromixis and occurs when the surface water, or epilimnion, is warmer than the deeper layers (or hypolimnion). As the warm water is less dense than the cool water, the two water masses do not mix well together. The lighter, warmer water forms a surface layer on the lake somewhat similar to that found when oil is poured on to water. The point where these two layers meet is known as the thermocline and is characterized by a rapid change in temperature with depth. Figure 2 shows a typical temperature/depth plot from Lake Malawi illustrating this condition.

Nutrients, particularly nitrogen and phosphorus, play a vital role in dictating the overall productivity of most biological systems and in lakes their availability frequently operates a control on the overall production of biological tissue or biomass. The main source of nutrients to the productive sur-

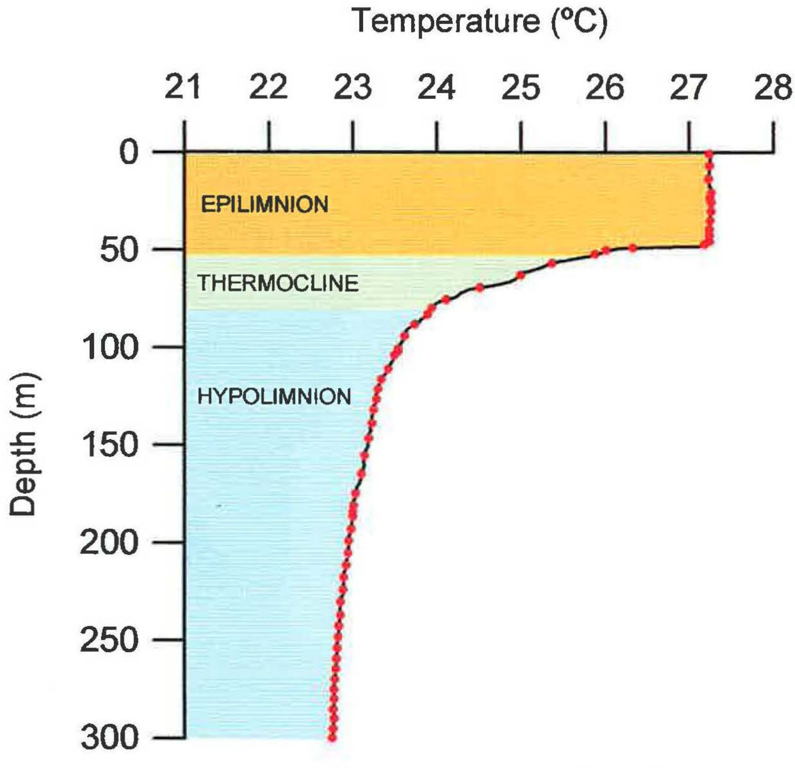
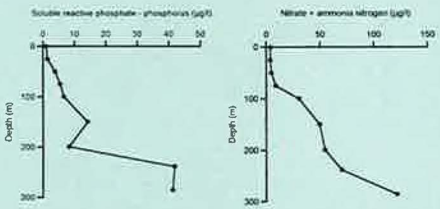


Figure 2—A typical temperature profile from Lake Malawi, 13 May 1992.

Box 3—The relationship between temperature, nutrients and photosynthesis in Lake Malawi

At the bottom of the food chain are the 'primary producers' and in a deep lake this role is carried out by the phytoplankton. These are microscopic plants which contain the green pigment chlorophyll. With this pigment they are able to absorb the energy of sunlight and use this to combine carbon dioxide (dissolved in large quantities in lakewater), water and nutrients and so produce biomass. This process is known as photosynthesis or primary production. All other organisms within the lake depend on this production of organic material either directly by feeding on phytoplankton or indirectly by feeding on organisms higher in the food chain. Fish populations, and the overall potential of the fishery in any lake, depend largely on the amount of primary production carried out by the phytoplankton. As mentioned above, the phytoplankton require sunlight to photosynthesize and this restricts them to a zone close to the water surface where sufficient light penetrates. Depending on the clarity of the water, sufficient sunlight will only penetrate to a certain depth, below which photosynthesis cannot take place. This depth is variable and depends on the amount incident light and on the clarity of the particular water body. In Lake Malawi, where the water is very clear, sunlight for photosynthesis can penetrate to approximately 40 m depth. If the vertical distribution of nutrients in Lake Malawi is examined (as shown below) it can be seen that nutrients are in much greater abundance in the deeper hypolimnetic water than in the surface epilimnetic water. This is a consequence of the constant sinking of biological tissue which, when it decays, releases nutrients into solution. These dissolved nutrients are prevented from returning to the surface because the thermocline restricts mixing between the two water masses. In tropical meromictic lakes this process can lead to a wide vertical disparity in nutrient levels as is shown for Lake Malawi below.

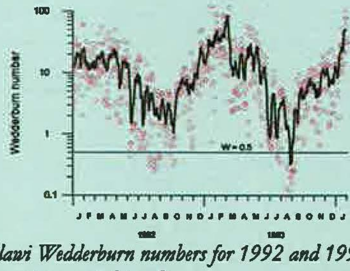


The distribution of nitrogen and phosphorus with depth in Lake Malawi. These profiles were sampled at the same time as the temperature profile given in Figure 2 (13 May 1992).

The reserves of nutrients below the maximum depth of photosynthesis (40 m in Lake Malawi) are therefore generally not available to the light-requiring primary producers. An understanding of the mixing processes between the epilimnion and the hypolimnion is critical to describe the dynamics of nutrient movement and therefore primary production. Description of the three-dimensional thermal structure indicates the distribution and intensity of the density barriers to mixing between the epilimnion and the hypolimnion. This can be used to understand nutrient distribution and the effect of this on overall production in the lake. The rate of primary production has a strong influence on fish production and overall fisheries potential. A description of the spatial and seasonal variation in production in a large water body like Lake Malawi would be an important target in any description of the productive basis of the fishery (see Box 4).

Box 4—Seasonal effects on the thermal structure of Lake Malawi and the effects of this on nutrient distribution

The degree of stability of the thermal stratification in any water body can be measured by the amount of energy required to overcome the disequilibrium and cause complete mixing. This depends on a number of factors principally, (1) the depth of the thermocline, (2) the temperature difference (and hence density difference) between the epilimnion and the hypolimnion, and (3) the strength of the wind causing water turbulence and therefore mixing. These three factors are often combined by lake scientists to produce a factor known as the Wedderburn number (named after Ernest M. Wedderburn, a Scottish hydrologist who worked in the early part of this century). Low values of the Wedderburn number (particularly values below 0.5) indicate periods when mixing of the two layers is likely. Using direct measurement of these three factors from a series of temperature profiles and wind data from a lakeshore meteorological station, a graph showing Wedderburn numbers calculated for each day throughout 1992 and 1993 for the lake is given below. This time series shows that, during the July/August period of each year, there are a number of days when the Wedderburn number is below 0.5 suggesting that there is a higher degree of mixing between the epilimnion and hypolimnion than at other times. These periods coincide with the cool season in the region, when epilimnion temperatures fall to close to the hypolimnion temperatures, thus reducing the density difference between the two layers. Coincidentally this season is also the windiest part of the year further increasing the likelihood of vertical mixing. The large scatter of points on the figure below is essentially a result of the variability of the daily wind values collected at the lakeshore meteorological station. The running average is used to help discern the seasonal pattern of variation in the Wedderburn number.



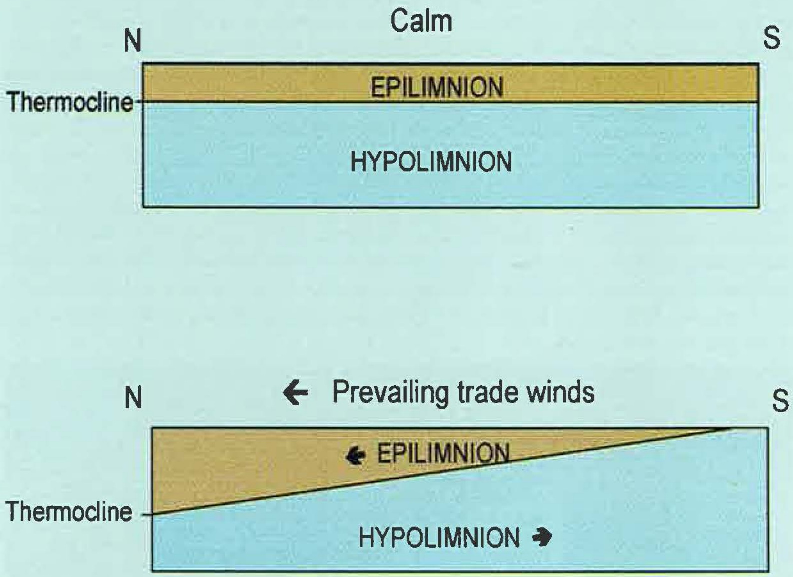
Daily values of Lake Malawi Wedderburn numbers for 1992 and 1993 including a nine-day running average to indicate the main seasonal trends.

The fact that the periods of the year where the Wedderburn number is lower than 0.5 are very short, means that complete mixing of the epilimnion and hypolimnion does not occur (or at least has never been recorded) in Lake Malawi.

It is known, however, that production in Lake Malawi is seasonal with higher values during the July/August period of each year when nutrient loading from the deeper nutrient-rich waters is assumed to be most prevalent. There is therefore a strong linkage between periods of high production and low Wedderburn numbers. From the figure it can be seen that Wedderburn values were lower in the middle of 1993 compared to the same period in 1992. This suggested a greater influx of nutrients into the epilimnion in 1993 and this was independently corroborated by the fisheries research team who found higher rates of primary production and fish larval production in that year, when compared to 1992.

Box 5—The formation of an epilimnetic wedge in Lake Malawi

As well as increased seasonal mixing at the thermocline boundary which results in upward movement of deeper hypolimnetic water (Box 4), a further process also acts to bring this water closer to the surface of the lake. Starting with a generalized model for stratified lakes illustrated below, this shows the effects of constant unidirectional wind on a thermally stratified lake. The wind results in surface water being transported to the leeward end of a water body. This causes the formation of what is referred to as an epilimnetic wedge, when deeper water is forced closer to the water's surface at the windward end of the lake. This upwelling of hypolimnetic water is known to occur in Lake Malawi during the windy July/August period of each year, and due to the prevailing monsoon winds being from the south or southeast the upwelling occurs in the southern part of the lake (Figure 3).



Schematic diagram showing the formation of an epilimnetic wedge as a result of unidirectional southerly winds.

face waters of Lake Malawi are the high levels of nutrients dissolved in the deeper waters of the hypolimnion (Box 3). Factors that affect the upward movement of these nutrients into the surface water are critical in developing an understanding of the productive basis of the lake (Boxes 4 and 5).

Remote sensing of Lake Malawi

The LARST NOAA satellite receiving station was located at Senga Bay, Malawi, the headquarters of the UK/SADC project. Details of the LARST NOAA receiving equipment sited at Senga Bay are given in Box 6. Remotely sensed data, captured and processed using the receiving station, were calibrated with *in situ* data collected during the research cruises on actual lake temperature values (see Box 2). It was decided to confine the study to data from one satellite, NOAA-11, the only NOAA satellite which passed over

Box 6—The LARST NOAA system at Senga Bay Malawi

The LARST system installed at Senga Bay is based on a Bradford University Remote Sensing Ltd PC-based receiving station. The system captures and processes data from NOAA satellites as they pass over the lake. The hardware comprises a motorized horn antenna, a receiver, and a PC computer and printer to process and display the data. The system is protected against local power supply instability and surges by uninterruptable power supply, line voltage conditioner and clean power system. Operator interaction is minimized by using a motorized antenna for tracking satellites across the sky. The operator uses simple software to identify the geographical area of interest and to specify the products required, which can be printed, archived or both. This takes a few minutes each week. No further interaction is required for day-to-day operations since the system software predicts the pass times and then captures, processes and prints the information automatically. In this way, production of useful information about lake surface temperature and water quality is fully automated and available daily. In research mode, further processing can be undertaken to examine, edit and enhance standard products or to generate new ones.

LARST NOAA receiver at Senga Bay, Malawi.

Lake Malawi during the night. Night-time images were preferred in order that the effects of warming of the lake surface by direct sunlight could be removed. Direct measurements of vertical temperature distribution showed that these day-time surface effects broke down during the night and that night-time surface temperature estimates were representative of conditions throughout the upper layers of the water column (see later). From May 1992 to September 1994 some 95 relatively cloud-free images were collected from NOAA-11 to give lake surface temperature images of Lake Malawi. After the initial calibration period the remotely sensed estimates of surface temperature proved reliable whenever it was possible to check surface temperature values using accurate thermometers.

The NOAA-11 data provided accurate, timely and reliable information on the surface temperature structure of Lake Malawi. The critical question is whether this two-dimensional view can lead to an understanding of subsurface temperature structure of a water body and can therefore be used to infer real limnological events.

An actual transverse section of Lake Malawi temperature structure is given in Figure 3 and this is based on a series of temperature profiles (indicated by the

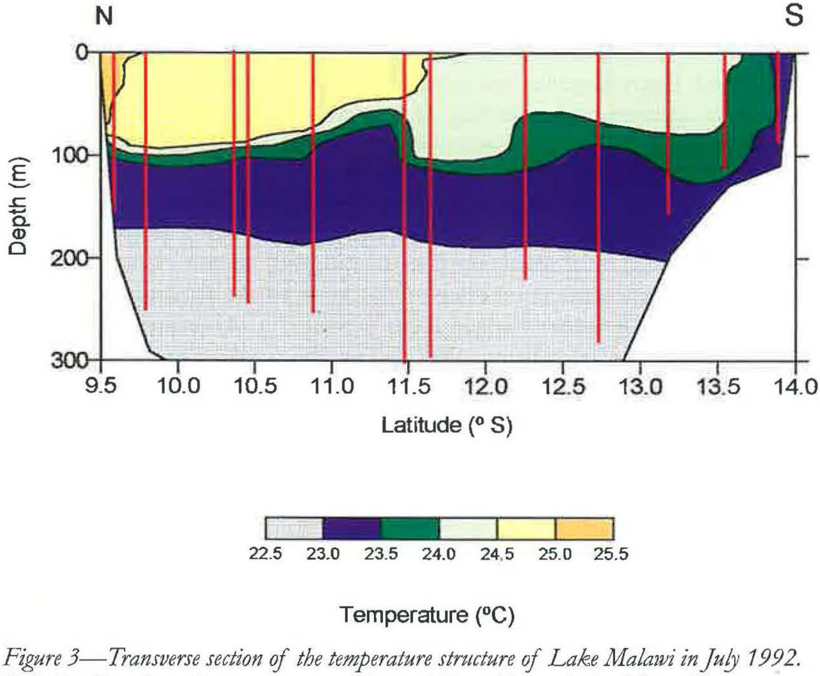


Figure 3—Transverse section of the temperature structure of Lake Malawi in July 1992. Individual locations of temperature profiles are indicated by vertical red lines. These correspond to positions indicated on Figure 4.

red-coloured vertical lines on the figure) collected during a full-lake cruise carried out in July 1992. This figure, therefore, shows the true three-dimensional structure of the lake and demonstrates that in July 1992 the thermal structure of the lake resembles that shown in a simplified form in Box 5, with the formation of an epilimnetic wedge and the surfacing of cool hypolimnetic water at the windward (southern) end of the lake.

A satellite image of Lake Malawi, captured on 24 July 1992, is shown in Figure 4. This image is concurrent with the directly derived longitudinal section of the temperature structure of Lake Malawi in Figure 3. Not only is there a strong correspondence between the directly measured temperatures at the surface and those obtained from the satellite-derived data, but the north–south pattern (the epilimnetic wedge) is also detected on the satellite image with surface water in the north being warmer than in the south of the lake. This confirms that the satellite image does contain substantial evidence of the three-dimensional structure of the lake.

Depending on the amount of cloud cover, a frequent series of images of the lake can be used to give a synoptic view of whole-lake processes. A fully automated satellite data reception and processing system installed at Lake Malawi provided a total of 76 acceptably cloud-free images of the whole lake, from May 1993 to August 1994. With these images and some prior knowledge of the temperature structure of the lake, a number of hydrological parameters could be observed. Box 4 describes the value of estimating the Wedderburn number in order to gain an understanding of lake-wide mixing processes. Figure 5 shows a repeated plot of the figure in Box 4 but this time the daily Wedderburn numbers, derived from satellite data for the period May 1993 to August 1994, are superimposed. Derivation of the satellite-derived Wedderburn number relies on knowledge of the surface temperature from the satellite image and wind data from the local government meteorological stations. It is also necessary to incorporate some knowledge of the depth of the thermocline and the hypolimnion temperature obtained from previous *in situ* measurements. The good agreement between the two data sets for the overlapping period of May 1993 to January 1994 strongly indicates that subsequent values for the Wedderburn number, derived from satellite data alone and unsupported by *in situ* measurements, are reliable. This data set could be continued indefinitely, at very low cost, and for all parts of the lake. The relationship between Wedderburn numbers, nutrient distribution and primary production is central to an understanding of the ecology of Lake Malawi (see Box 4).

Other ephemeral hydrological phenomena can also be observed, and these may have important consequences for the movement of nutrients within the lake. For example, October 1993 satellite images indicated there was a notable upwelling of colder water in the northern part of the lake (Figure 6). This coincided with a period when later *in situ* measurements indicated there had been relatively high productivity of phytoplankton and fish larvae in the north of the

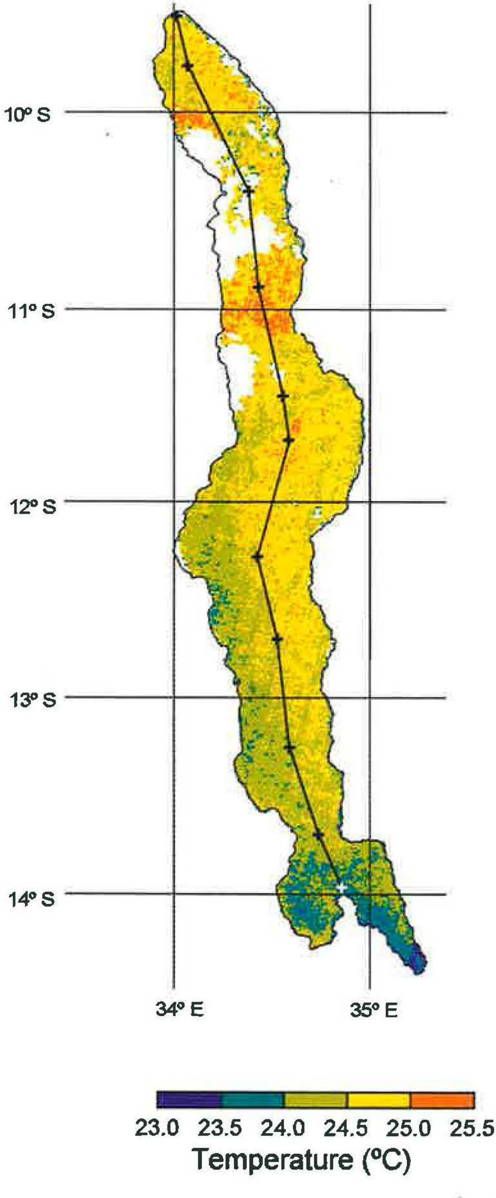


Figure 4—Satellite image of lake surface temperature of Lake Malawi on 24 July 1992. Symbols indicate locations of temperature profiles made during a full-lake cruise in July 1992 and correspond to the profiles indicated on Figure 3.

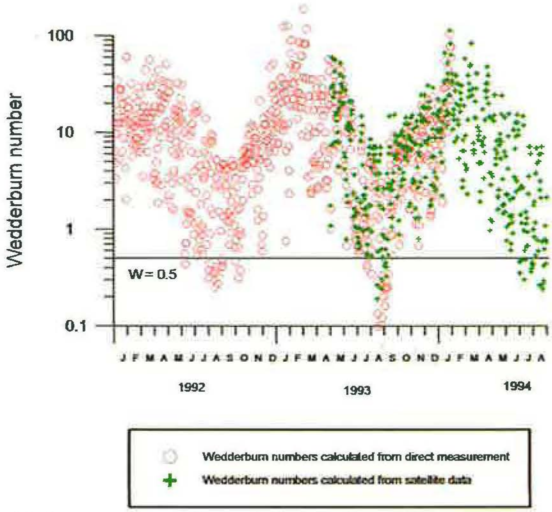


Figure 5—Wedderburn numbers calculated from in situ *measurements (red circles) and from satellite surface temperature data (green crosses) combined with wind data from the Malawi Meteorological Department.*

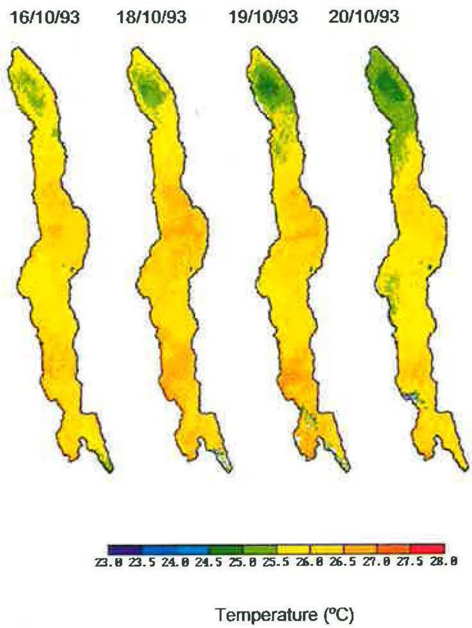


Figure 6—Probable cold water upwelling event detected in the north of Lake Malawi.

lake. It is likely that these events were interconnected. If the link between water temperature and fish larval growth was more closely observed and shown to be consistent, this would lead to the development of an important management tool where, generally, recruitment of fish larvae into the commercial fishery for adult fish, is difficult to predict.

Summarizing for Lake Malawi it can be seen that the satellite-derived night-time surface temperature yields a large amount of information of the thermal density structure of the lake. This is likely to affect the distribution of nutrients and therefore have a profound effect on lake productivity. The availability of concurrent satellite-derived and *in situ*-derived data for Lake Malawi has allowed the calibration of the remotely sensed temperature estimates and the satellite data reception (LARST) station can now be operated at low cost to give a large amount of reliable and usable data whereas collection of *in situ* data on Lake Malawi is extremely costly. Satellite imagery will not replace *in situ* measurements which give greater detail but they do enable the production of a reliable, cheap and complete data set. The annual running cost of a LARST NOAA system is approximately US$ 10 000 and it can be operated by locally trained staff with low-level support from the Natural Resources Institute in the UK.

Interpretation of imagery does, of course, require a higher level of training but this can be incorporated within the duties of professionals at the national fisheries organization, for example. Continuation of satellite collection and archiving should be a priority in order to produce a long-term data series on Lake Malawi. This will allow further studies on the lake to be placed within a long-term context.

Other African freshwater systems

There are a number of deep meromictic lakes in Africa apart from Lake Malawi, most notable amongst these are Lakes Tanganyika and Kivu (Table 1). The lake surface temperature image of Lake Tanganyika compared with a contemporaneous image of Lake Malawi (Figure 7) shows a very similar pattern of surface distribution of temperature, indicating the formation of an epilimnetic wedge in Lake Tanganyika during the period of southeast trade winds. The overall higher temperature of Lake Tanganyika compared to Lake Malawi is expected from its relative proximity to the equator. In addition to the meromictic lakes there are many lakes with a variable and somewhat unpredictable vertical mixture regime (including Lakes Victoria, Kariba, Chad, Volta and Turkana). Mixing processes in these highly dynamic lakes have proved difficult to elucidate by the usual method of studying a number of fixed stations, and it is likely that a series of satellite images of lake surface temperature would be a major piece of evidence in the understanding of whole-lake mixing regimes. Most African lakes have vitally important fisheries and all the lakes listed in the

Table 1—African water bodies of > 1000 km². Fisheries statistics should be treated with caution as for many lakes the fisheries statistics for more than one country are included. These are not necessarily for the same calendar year and in this case the mean year is given.

Water body	Lake or reservoir	Surface area (km²)	Yield (t/yr)	Year
Victoria	Lake	68 800	251 000	1986
Tanganyika	Lake	32 900	104 000	1988
Malawi	Lake	28 800	51 000	1986
Chad	Lake	22 198	87 000	1975
Volta	Reservoir	8 270	39 500	1979
Turkana	Lake	7 570	7 500	1986
Nasser/Nubia	Reservoir	6 216	34 500	1981
Kariba	Reservoir	5 364	14 500	1981
Albert	Lake	5 270	15 000	1987
Mweru	Lake	4 650	13 800	1983
Kafue Gorge	Reservoir	4 340	9 000	1982
Tana	Lake	3 500	50	?
Cabora Bassa	Reservoir	2 665	4 300	1982
Kivu	Lake	2 370	3 500	1987
Rukwa	Lake	2 300	6 000	1978
Edward	Lake	2 300	13 000	1988
Maji Ndombe	Lake	2 300	1 500	1982
Mweru Wa Ntipa	Lake	1 600	11 000	1982
Kossou	Reservoir	1 600	7 500	1980
Jebel Aulia	Reservoir	1 500	8 200	1982
Kainji	Reservoir	1 270	4 500	1978
Fitri	Lake	1 200	?	?
Abaya	Lake	1 164	100	1981
Wetland	**Swamp or floodplain**	**Area (km²)**	**Yield (t/yr)**	**Year**
Chad Basin	Floodplain	370 000	?	
Likouala	Floodplain	40 000	?	
Central Zaire Basin	Floodplain	37 870	?	
Sudd	Swamp	32 000	100	1982
Ovambo	Floodplain	23 000	?	
Niger Central Delta	Floodplain	20 000	?	
Okavango	Swamp	20 000	500	1985
Bangweulu	Swamp	12 271	?	
Lualaba	Floodplain	11 840	?	
Barotse	Floodplain	10 900	5 200	1982
Mbandaka Area	Floodplain	10 415	2 880	1986
Lukanga	Swamp	8 000	2 601	1982
Yaeres	Floodplain	4 600	?	
Kilombero	Floodplain	4 000	?	
Niger	Floodplain	3 000	?	
Lorian	Swamp	2 590	?	
Oueme	Floodplain	2 000	?	
Benue	Floodplain	1 810	?	
Malagarasi	Swamp	1 800	?	
Rufiji	Floodplain	1 450	?	
Kitangiri	Floodplain	1 095	?	

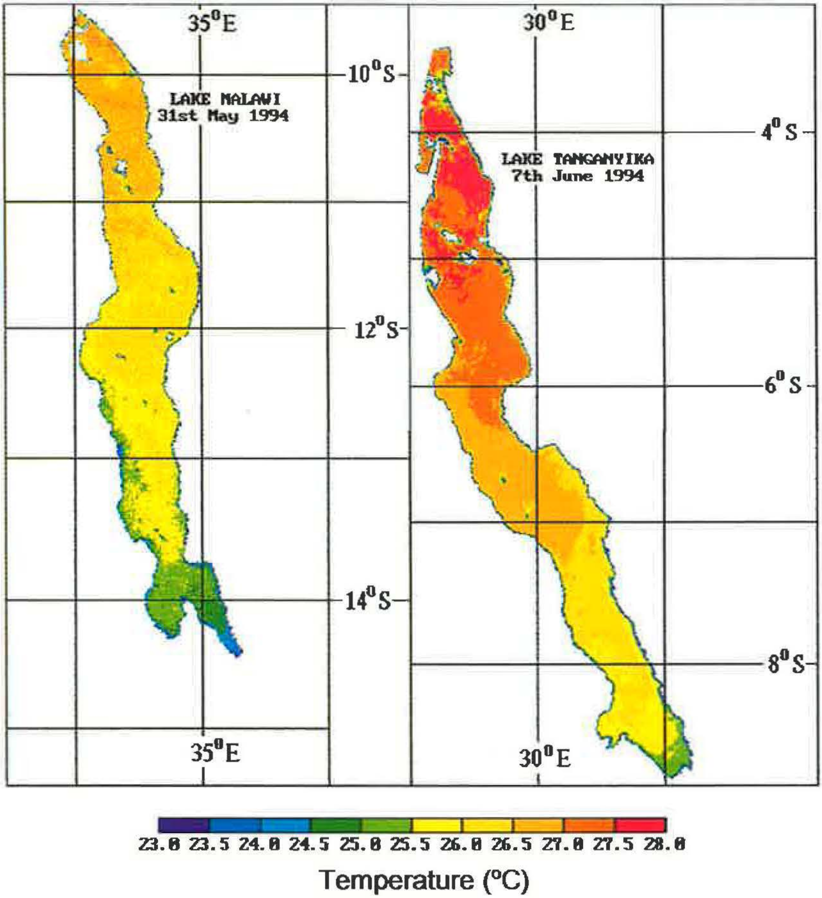


Figure 7—Lake surface temperature distribution on Lakes Malawi and Tanganyika during the period of the southeast monsoon winds.

table below are deemed sufficiently large (>1000 km^2) to allow the observation of spatial and temporal patterns of lake surface temperature using data from NOAA satellites. This would provide a useful set of information for considering the productive basis of these lakes.

Other information on African freshwaters that would particularly lend themselves to analysis by remote sensing, and which could be carried out using existing satellite systems, include monitoring of the extent of open water and the distribution of floating aquatic vegetation. For shallow lakes, and particularly for temporary water bodies (swamps and floodplains; Table 1), it is possible to obtain accurate measurements of the horizontal extent of water (using channels

2, 4 and 5 of the AVHRR; see Box 2), and therefore to monitor seasonal changes in size of the water body. Temporary water bodies are little studied and data on fisheries production are limited and likely to be inaccurate. There is little doubt, however, that they are of great economic importance directly to the local populations as well as being sites of high biological diversity and therefore of importance as conservation areas. The monitoring of seasonal variations in extent of open water also has important contributions to make in the fields of climatic monitoring and flood control.

Floating aquatic vegetation is an important management issue in African lakes and reservoirs. As well as being a hazard to navigation, its presence at the surface disrupts the passage of light to phytoplankton and this in turn leads to reduction of dissolved oxygen in the water which can cause fish kills. This problem is increasing in Africa as nutrients increase in some waters due to sewage and atmospheric pollution, encouraging the development of aquatic vegetation. The problem is exacerbated by new species of floating vegetation that have been accidentally introduced and which flourish in the absence of natural predators (e.g. the water hyacinth introduced into ornamental ponds in Africa and now naturalized in many freshwaters). It is possible to measure and monitor the distribution of floating aquatic vegetation (using the visible band AVHRR channels 1 and 2; see Box 2).

Future developments in remote sensing

It seems highly likely that for the foreseeable future the availability of data from sensors similar to those carried by the current series of NOAA satellites is assured. At the time of writing (November 1994) the next NOAA satellite is about to be launched and the National Aeronautics and Space Administration (NASA) has made a strong commitment to this series at least until the next century when the European Space Agency has agreed to continue to operate AVHRR-type sensors on board the Meteorological Operational (METOP) series of satellites. This is designed to give similar coverage to that currently available from NOAA, allowing for the production of long-term data series.

During the period of the project a more direct method was attempted for examining primary production in Lake Malawi. This was to endeavour to detect chlorophyll (the green pigment in all photosynthetic plants) using an index derived from channels 1 and 2 of the AVHRR (see Box 2). The index was found to be insufficiently sensitive to detect chlorophyll in Lake Malawi where levels are usually as low as 1 mg of chlorophyll per cubic metre of water. Sensors specifically designed to detect chlorophyll are, however, much more sensitive. There is a great deal of interest in the Seastar satellite, due to be launched in 1995, which carries the SeaWiFS (Sea-viewing Wide Field-of-view Sensor), specifically designed to measure water-borne chlorophyll at levels down to 0.05 mg per cubic metre. The data from this satellite can be locally received using a slightly modified

Box 7—The future of remote sensing in the management of freshwater systems
The Seastar satellite is due to be launched in early 1995 and the SeaWiFS (Sea-viewing Wide Field-of-view Sensor) carried onboard is designed to give details of ocean colour. This sensor was fundamentally designed to be complementary to the AVHRR sensor, with the same resolution, similar data structure, similar orbital characteristics and the same data transmission technology. Such similarities will allow SeaWiFS image data to be collected using currently operational NOAA receivers (with some minor modifications). The SeaWiFS data is likely to be encrypted when received by a local receiving station. Research users can obtain free decryption once the data is over two weeks old and commercial users can obtain a licence that will allow immediate decryption of the received data. Further satellites, including EOS (Earth Observing System), ADEOS (Advanced Earth Observing System), ERS-2 (European Remote Sensing Satellite-2) and ENVISAT (Environmental Satellite) are expected to carry sensors that build on the capability of SeaWiFS and the AVHRR to provide an increasing amount of information on the aquatic system. By using data from multiple sensors it should be possible to combine water colour data to give chlorophyll distribution in freshwaters, along with water clarity data (the Diffuse Attenuation Coefficient that defines the light regime in water bodies) to give modelled estimates of primary production. These will be subject to a number of errors based on assumptions in the models but will, nevertheless, give a vast amount of information on the pattern of photosynthesis in the world's water bodies. The wide and repetitive look offered by satellites provides the chance to consider the distribution of primary production at spatial and temporal scales never before possible. For Further reading see Hooker, S.B., Esaias, W.E., Feldman, G.C., Gregg, W.W. and McClain, C.R. (1992) *SeaWiFS Technical Report Series. Volume 1: An overview of SeaWiFS and ocean colour.* National Aeronautics and Space Administration technical memorandum 104566. Goddard Space Flight Center, Greenbelt, Maryland 20771.

LARST receiving station and have great potential to describe biological processes in large water bodies (Box 7).

Much of the work described above is dependent on methods to collect and handle the large amount of data that can be generated by satellite systems. Computer software packages known as geographical information systems (GIS) offer a way of analysing and presenting these data. Presentation of data to non-specialists in remote sensing (e.g. fisheries managers) requires careful consideration.

Conclusions

A continual and rigorous programme of ground truthing is necessary in order to both convince the non-specialist of the reliability of the data presented, as well as to maintain a constant and evolving calibration of the satellite-derived estimates. Remote sensing has much to recommend it as a method, its principal value being that it is a relatively inexpensive way of offering a synoptic view. The more it can be shown (to the end user) to be calibrated with independently collected data the more it will be incorporated into any research or management programme. Remotely sensed data have already shown some proven benefits to ocean fisheries management and the indications are that they will become increasingly useful in the management of freshwaters and freshwater fisheries. As described above, similar methods to those presented in this publication on Lake Malawi could be adapted and applied to many other freshwater systems.

Further reading

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Wooster, M.J., Sear, C.B., Copley, V.R. and Patterson, G. (1994) Monitoring Lake *Malawi using real-time remote sensing.* (Final report of the remote sensing component of the UK/SADC Pelagic Fish Resource Assessment Project.) Chatham, UK: Natural Resources Institute. (unpublished)

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Glossary

Epilimnion	Upper layer in a vertically stratified water column
Hydrology	Study of the distribution, movement and effects of water in the land areas of the Earth
Hypolimnion	Lower layer in a vertically stratified water column
Limnology	Study of the ecology of lakes and other freshwaters
Meromixis	Condition of permanent thermal stratification in a water column
Photosynthesis	Process by which green plants use the energy of light to convert inorganic carbon to organic carbon
Phytoplankton	Microscopic plants suspended in a water body
Primary production	Production of organic material by photosynthesis
Real-time	Simultaneous recording and reporting of events
Satellite	Earth-orbiting platform able to carry onboard various forms of instrumentation
Sensor	Camera-like device for detecting radiation in part of the electro-magnetic spectrum
Swath	Path on the Earth's surface that can be imaged by a satellite on any particular overpass
Thermocline	Zone of rapidly changing temperature with depth, in a stratified water column
Upwelling	Movement of deep water to the surface in a lake or ocean