IMPACT OF STRATIFICATION ON NUTRIENT CONCENTRATION IN MANASBAL LAKE, KASHMIR

Dissertation Submitted

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CERTIFICATE

Certified that the work presented in this dissertation ***entitled "Impact of Stratification on Nutrient Concentration in Manasbal Lake, Kashmir"*** by **Tabasum Yaseen** has been carried out under my supervision and the same has not been submitted elsewhere for the degree. Certified further that the candidate has fulfilled all the conditions necessary for the M.Phil. degree examination of University of Kashmir. The dissertation is worthy of consideration for the award of M.Phil. degree in Environmental Science.

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DEDICATED
TO
MY
BELOVED
PARENTS
&
TEACHERS

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Tabasum Yaseen

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CHAPTER – 1

INTRODUCTION

Lakes are aquatic ecosystems broadly distributed in the continental terrestrial surface (Downing *et al*., 2006) and make up about 0.008% of the total distribution of water on the earth's surface. They are useful as a source of water, habitat for aquatic organisms, recreational activities etc. Lakes can also to help protect water quality by constituting a well-recognized recipient environment for organic and inorganic matter washed from the watershed by inflowing streams (Sobek *et al*., 2005) so that outflowing streams often carry less of these pollutants (Michaud, 1991).

Temperature measurements occupy a central position in limnology. The temperature of water in a lake changes with the seasons and often varies with depth. During spring and summer, the sun warms the upper waters. As the sun continues to warm the lake surface, the temperature differences increase between the surface and deeper waters. Water temperature plays a driving role in most physicochemical processes in lakes, e.g. the presence and duration of ice-cover and thermal stratification (Fang and Stefan, 1999), dissolved gas concentrations and associated redox potential, and sediment–water nutrient dynamics (Jankowski *et al*., 2006; McKee *et al*., 2003). Thermal stratification is complex integration of multiple forcing components such as mixing rates, vertical dimensions of layers, layer temperature, the temporal duration of stratification, basin morphometry (Ford and Stefan 1980), hydrology and, most important, meteorological conditions (Effler *et al.* 1986, Harleman 1982, Owens and Effler 1989). In stratified lakes, gradients of temperature, light and oxygen have been reported to influence the vertical flux of nutrients (Kufel and Kalinowska, 1997; Kleeberg and Schubert, 2000) as well as the vertical distribution of plankton communities (Reynolds, 1992). In addition to gradients of dissolved nutrients, a large accumulation of particulate nutrients may also occur in the metalimnion (Rodrigo *et al.*, 2000).

The water bodies that reflect thermal stratification are categorised as amictic, monomictic, dimictic or oligomictic on the basis of the frequency of occurrence of thermal stratification. The amictic lakes remain always thermally stratified, while the ologomictic lakes circulate only rarely after a gap of several years. The monomictic lakes reveal a prolonged stratification followed by a short circulation period each year. In case of dimictic lakes two circulation periods alternate with two stagnation periods each year.

Understanding the role that vertical stratification plays in regulating the ecology of lakes and reservoirs is a cornerstone of modern limnology (e.g., Lerman *et al*.,1995; Lampert and Sommer, 1997; Wetzel, 2001; Kalff, 2002). In thermally stratified lakes, the differentiation into a nutrient-enriched hypolimnion and a nutrient-depleted epilimnion is a common feature, and the vertical mixing between both layers affects geochemical and biological processes and, as such, the water quality. The hypolimnetic enrichment of solutes is a common feature among thermally stratified eutrophic lakes (Wetzel 1983). Among these are ammonium and dissolved methane, both of which are inert under anoxic conditions. Their distribution within the hypolimnion is governed by release and mixing processes. Consequent upon the variation in the occurrence and duration of stratification, spatial and vertical variations in the ecological features of the concerned water body are expected to vary in case of the different categories of stratified lakes.

The valley of Kashmir has a number of water bodies spread over its length and breadth. While most of them are very shallow and hence do not show any permanent stratification phenomenon, some have been reported to stratify. Lake Manasbal ($34^{o}14^{'}40^{''}$– $34^{o}15^{'}20^{''}$N and $74^{o}39^{'}00^{''}$–$74^{o}41^{'}20^{''}$E and 1583 m amsl) has been reported to be the only warm monomictic lake in the valley (Hutchinson, 1957). The water body has been found to stratify during March – November/December and circulate for the brief period of December – February. The lake has been an important tourist spot, besides being a source of commercial fishing, and a number of economically important plants. Keeping in view, the economic and ecological importance of the lake, it was decided to have an insight into the process of thermal stratification in this water body and assess the impact of the thermal stratification on the nutrient distribution in it. The data collected during the year- long study are presented in the form of the present M.Phil. dissertation.

CHAPTER – 2

REVIEW OF LITERATURE

Fresh water resources are most precious to earth: they are the basic ingredient to life. Increased demands on the resources have impacted heavily on natural aquatic ecosystems. The living communities of inland waters, their functional relationships, productivity, physical, chemical environment are all dealt in aquatic ecology/ limnology. Inland waters, lakes in particular, afford excellent and easily available opportunity for studying the structural and functional processes of an aquatic ecosystem. The interdependence of aquatic and terrestrial ecosystems, including interactions by man, finds its most sensitive responses in lakes. The rapid changes that have been observed in the last few decades in chemical and biological properties of many water bodies reflect the human influence on the environment and are a by-product of positive energy dissipiation.

A wealth of literature has been developed on almost all aspects of inland aquatic ecosystems during the last 50 years throughout the world. In the following pages, important contributions made in the field during the last few decades on the limnological aspects are reviewed.

Kaul (1977), while discussing limnology of Kashmir lakes with reference to trophic status ansd conservation, reported that despite the increasing cultural influences and sewage contamination, the valley lakes of Kashmir are low in nitrate- nitrogen and phosphate- phosphorus which he attributed to the locking of phosphates and nitrates in the macro- vegetation.

Qadri and Yousuf (1978), while studying the seasonal variations in the physico- chemical factors of Manasbal lake, Kashmir, revealed that the lake remained stratified for about nine months from March to November. The study further concluded that the thickness of the thermocline, varied continuously from the start to the end of stratification and the thinning process of the thermocline has considerable effect on the physical and chemical features of the three layers of water, which in turn influence the biotic community.

Yousuf (1979) studied the limnology and fisheries of Manasbal lake and revealed that the light penetration of water varied in close relationship with the seasonal thermal structure of water in the limnetic zone, and registered lowest values at the time of the breakdown of stratification. In another publication (Qadri and Yousuf, 1980) observed that the deeper layers of water were less alkaline, containing large quantities of CO_2 and HCO_3^- of Ca^{++} and Mg^{++} as compared to the upper layers. In further studies, Yousuf and Qadri (1981) recorded a clinograde depth distribution curve of O_2, with the hypolimnion getting depleted of this gas during late stagnation period. In (1985) the same authors, while performing futher studies in the present lake revealed that the viscosity and density of water changes rapidly in the thermocline zone during thermal stratification, due to a quick decrease in temperature with the depth. The study also concluded that the changes in viscosity and density help in the temporary checking of the settling materials, including bacteria, thus offering better feeding opportunities to the zooplankton and possibly resulted in the concentration of zooplankton in this zone. In another study (Yousuf and Mir, 1994) reported that the distribution and abundance of rotifers was closely associated with thermal stratification of the lake, which also effects the vertical distribution of gases and nutrients. Yousuf *et al*. (1986) studied limnological features of Nilnag lake, Kashmir and observed the mesotrophic nature of lake. The study also revealed that the lake does not resemble to a greater extent to other high altitude lakes of Kashmir which are mostly oligotrophic and the concentration of nutrients in the lake is influenced by the allochthonous material. Yousuf and Shah (1988) studied comparative limnology of some fresh water habitats of Kashmir and related the higher concentration of nutrients in springs to lesser biological activity.

Khan (1979) reported that in Manasbal lake a distinct stratification in alkalinity occured due to increased photosynthetic activity which converted bicarbonates to carbonates. According to him ecological changes in the ecosystem were prevalence of anoxic hypolimnic water during major part of the year. In (1984) the same author, while studying primary productivity and some hydro-chemical aspects of polluted water body Trigam Sar, observed a weak thermal stratification with maximum surface temperature of $32.2^{o}C$ in the water body. In another paper (Khan, 1986) studied Lake Naranbagh and reported the cation and anion in the lake spectrum as $Ca^{2+} > Mg^{2+} > HCO_3^{-} > SO_4^{2+} > Cl^{-}$.

Wanganeo (1984), while studying primary production characteristics of a Himalayan lake in Kashmir concluded that the Lake Manasbal is the only lake in the region with a true thermal stratification during summer. In another publication, Zutshi and Wanganeo (1984) revealed that the increased inputs of phosphorus from the catchment determined the overall ecological stability of the ecosystem. In (1989) the same authors studied the nutrient dynamics and trophic status of Kashmir lakes and reported that the net balance for phosphorus and nitrogen was much higher in urban lakes in comparison to rural lakes. The authors stressed the use of nutrient load model for ecological monitoring. In another paper, Zutshi (1989) studied the limnology of high altitude lakes of Himalayan region and reported that the lakes remained thermally stratified between August and September and developed a stable thermocline.

Singh *et al.* (1980), while working on the limnology of shallow water zones of lakes in Kumaun Himalaya, observed that in stratified lakes anoxic condition occurs in bottom waters and the high CO_2 content in the bottom waters leads to higher bicarbonate content.

Knowles *et al.* (1981) studied nitrous oxide concentrations in lakes which varied in size, depth, and trophic state. The study revealed that nitrous oxide (N_2O) concentrations were strongly influenced by oxygen concentration. High concentrations of N_2O were found in the metalimnion of a eutrophic lake during early spring stratification when hypolimnetic O_2 and NO_3^- were already being depleted.

Taggart and McQueen (1981) worked on hypolimnetic aeration of a small eutrophic Kettle Lake and reported that during the summers total Kjeldahl-N and NH_3-N slowly increased in the hypolimnion, while NO_3-N concentration remained low.

Tipping and Woof (1983) studied seasonal variations in the concentrations of humic substances in a soft water lake and reported that humic substances accumulate in the hypolimnion due to the anaerobic decomposition of the settled particulate organic matter.

Numberg (1984), while investigating the prediction of internal phosphorus load in lakes with anoxic hypolimnion, observed that the ammonium and dissolved inorganic phosphorus concentrations are influenced by release from the sediments.

Coulter (1991), while working on Lake Tanganyika, revealed that permanent thermal stratification prevents the lake from full circulation.

Jensen *et al.* (1992) worked on the iron: phosphorus ratio in surface sediments and assessed its role as an indicator of phosphate release from aerobic sediments in shallow lakes. The results of the study revealed that a ratio of iron: phosphorus by weight of 15 in oxidized sediment would be able to control release of SRP (soluble reactive phosphorus) to the overlying water column if the pH of the sediment surface is less than 8.0.

Plisnier (1993) characterized the Lake Muhazi as a shallow lake with a rather unstable diurnal stratification and with slight differences in mixing regime between its deepest eastern part and its shallowest western part.

Joshi and Bisht (1993) conducted study on physico-chemical characteristics of western Ganga Canal of Haridwar. The findings revealed that the high value of CO_2 at bottom zones was related with higher rate of decomposition of organic matter and high turbidity.

Kebede and Belay (1994), while studying phytoplankton of Lake Awassa (Ethopia), reported the presence of anoxic water in the hypolimnion. The findings indicated that stressed conditions are because of high O_2 consumption by decomposition of organic matter and respiration of organisms in deeper waters in the absence of freely circulating water.

Nurnberg (1995) studied the anoxic conditions in lakes and reported that in warm monomictic lakes, the oxygen consumption in the aphotic layer leads to an oxygen deficit in the hypolimnion during the stratified period when ventilation is impeded because of the presence of a thermocline.

Larson *et al.* (1996) studied the water quality and optical properties of Crater lake, a deep ultraoligotrophic caldera (depth, 594 m) lake in the Southern Cascade Mountain Range of Oregon State, between 1983 and 1991. The results of the investigation indicated that most of the lake volume was a cold hypolimnion. The results further indicated that the lake was slightly basic, but alkalinity and conductivity were slightly elevated near the lake bottom, while nitrogen and phosphorus were low in concentration.

Pathak and Bhatt (1997) studied drainage basin dynamics and related physico-chemical limnology of the mountain streams and reported that the concentration of Ca^{2+}, Mg^{2+}, HCO_3^-, and SO_4^{2-} were inversely proportional to the quality of water during the catchment, while peaks of Na^{2+} were related with rainfall and leaching from the agricultural land.

Lossow *et al.* (1998), while working on lake restoration by artificial aeration with the use of wind energy in the heavily eutrophic Lake Starodworskie, suggested that there was a slight increase in the temperature of hypolimnion and oxygenation improvement during summer and considerable in the other seasons. Moreover, the content of organic compounds and nutrients (phosphorus) decreased.

Scheffer (1998), while investigating the ecology of shallow lakes, concluded that in stratified lakes phytoplankton takes up epilimnetic mineral nitrogen and transports it to the hypolimnion through sedimentation. Further, the study revealed that the nitrogen may accumulate in the hypolimnion during stratification periods, while in the epilimnion nitrogen deficiency may occur if resupply from the inflows is limited.

Gervais *et al.* (1999), while working out the basic limnological characteristics of the shallow eutrophic Lake Grimnitzsee (Brandenburg, Germany), concluded that although the lake is usually polymictic, but in 1994 and 1995 relatively long summer the lake remained stratified for quite some time due to very high global radiation input. Results of the study on nutrient concentration, light climate, oxygen status, phytoplankton biomass and the species composition of littoral diatoms characterized the lake as eutrophic. Further, results of the study indicated that the polymictic character of the lake was due to the multiple developments of aerobic or anaerobic strata above the sediment.

MacIntyre *et al.* (1999) made studies on boundary mixing and nutrient fluxes in Mono lake, California. The findings indicated that the density stratification suppresses vertical transfer between bottom and surface waters, often resulting in a nutrient rich but light-limited hypolimnion in stark contrast to an epilimnion rich in light but poor in nutrients.

Plisnier *et al.* (1999) worked on limnological annual cycle inferred from physical-chemical fluctuations at three stations of Lake Tanganyika. The study revealed that the turbidity changes are caused by internal waves linked to non-random patchiness in nutrients and organisms. The lake water generally showed oligotrophic characteristics near the surface but had high concentrations of nutrients in deep water.

Nishri *et al.* (2000) performed the analysis of the physical regime and the respective biogeo-chemical processes in lower water mass of Lake Kinneret. They found that with the onset of thermal stratification, hypolimnetic dissolved oxygen got gradually depleted, which was followed by nitrate reduction and the steady increase of sulfide concentrations due to microbial sulfate reduction. The study further revealed that the reducing conditions typically favoured the accumulation of ammonium and phosphate, both of which originate from organic matter decomposition and sedimentary release.

Sondergaard *et al.* (2000), while working on hypolimnetic nitrate treatment to reduce internal phosphorus loading in a stratified lake, concluded that the presence of nitrate acted as a barrier in reducing the internal phosphorus load of the hypolimnion in Lake Lyng (Denmark).

Luglie *et al.* (2001), while studying the trophic status of Bidighinzu Reservoir, reported that the nitrate-nitrogen was higher than ammonium-nitrogen in late winter and early spring, whereas ammonium-nitrogen was higher than nitrate-nitrogen during stratification (autumn), due to a marked hypolimnic deoxygenation.

Wetzel (2001) hypothesized that the thermal stratification affects vertical water quality distribution in lakes, especially in eutrophied lakes. According to him surface waters were warm and become less dense and the relative thermal resistance of mixing increases markedly and a difference of only a few degrees is then sufficient to prevent complete circulation.

Detenbeck *et al.* (2002) studied effects of agricultural activities on water quality of Prairie wetlands and reported that nutrient dynamics changes more in response to changes in water level and vegetation structure than to increased nutrient inputs.

Ford *et al.* (2002) studied the methane and oxygen dynamics in a shallow floodplain lake in relation with periodic stratification. The results depicted that the water mixing is a physical control that may be driven by hydrology, depth, wind forces, temperature or salinity inputs. It was observed that water stratification by physical controls also influences the vertical profile patterns of biogenic gases.

Gunkel and Casallas (2002) examined the limnology of an equatorial high mountain lake -Lago San Pablo, Ecuador. They observed that the lake is monomictic one with no true thermal stratification, with only 1-2 °C difference between the epilimnion and hypolimnion; overturn is achieved by strong winds during the dry summer period and the lake undergoes atelomixis. The stratification phase is characterized by an oxygen deficit in the lower part of the hypolimnion.

Moser *et al.* (2002) investigated the eutrophication of a remote Boreal lake. According to the study total phosphorus is likely to be increased as a result of enhanced internal cycling of phosphorus either due to increased thermal stratification in response to warmer summer temperatures or decreased meromictic stability.

Pandit and Yousuf (2002), while studying six Himalayan lakes, reported that the best chemical indicator of the trophic status of these aquatic systems was total phosphorus and total dissolved inorganic nitrogen in the epilimnetic layers.

Rogora *et al.* (2002) reported that the anoxic conditions in Lake Alserio characterise the hypolimnic waters for a prolonged period during summer stratification, with a consequent high phosphorus release from the sediments.

Veronesi *et al.* (2002) made a detailed study on phosphorus, carbon and nitrogen enrichment during sedimentation in a seasonally anoxic lake (Lake Lugano, Switzerland) and recorded that calcite precipitation in the epilimnion and its re- dissolution in the hypolimnion may actively transport phosphorus from surface to deep layers.

Ambrosetti *et al.* (2002), while studying residence time and physical processes in Lakes, found that wind is a major factor influencing the thermal stratification occurring in a water body. They pointed out that the wind blowing across the surface of the lake, transfers part of its momentum to the water mass, generating a complex set of movements (turbulence, waves, currents), producing active kinetic energy and drive mixing of the water column.

Kisand and Noges (2003) studied the release of phosphorus from the surface sediments of two shallow eutrophic lakes and observed that anoxia is likely to occur not only in the sediments of stratified lakes with anoxic hypolimnion, but also in the sediments overlaid with oxic water.

Friedrich *et al.* (2003) investigated the nutrient uptake and benthic regeneration in Danube Delta lakes. The study revealed that the benthic release of ammonia and silica increases from June to September.

Ruhland *et al.* (2003) analyzed limnological characteristics of 56 lakes in the Central Canadian Arctic Treeline Region and found out that the increase in major ions and related variables (dissolved inorganic carbon, dissolved organic carbon) was high in Boreal forest sites in comparison to Arctic Tundra sites which they related to differences in climatic factors.

Salmaso *et al.* (2003) investigated the vertical mixing and trophic status in deep lakes in temperate climates and recorded that when there is an incomplete overturn, the renewal time of the hypolimnetic waters is low, favouring an increase in algal nutrients (phosphorus, nitrogen and silica compounds) as well as (in calcareous lakes) dissolution of $CaCO_3$ from settling particles.

George and Hurley (2003) studied the impact of climate change on the dynamics of thermally stratified lakes. The study proved that the critical factors influencing the hydraulic responses of the selected lakes were the size of basin and the ratio of epilimnetic to hypolimnetic volume.

Schernewski (2003), while studying nutrient budgets in a eutrophic, stratified Baltic Lake, found that during stratification there are low concentrations of calcium, total phosphorus, and ammonium ion in the epilimnion and enrichment in hypolimnion.

Huszar *et al.* (2003) investigated the steady-state assemblages of phytoplankton in four temperate lakes (NE U.S.A.) and pointed out that prolonged period of both mixing and stratification maintain dominant assemblages.

Selig and Schlungbaum (2003), while characterising and quantifying phosphorus release from profundal bottom sediments in two dimictic lakes during summer stratification, reported that the soluble reactive phosphate (SRP) and ammonium ion (NH_4^+) were released from the anoxic sediment into the water column in Lake Dudinghausen and Lake Tiefer. The sediment released NH_4^+ and SRP only when oxygen and nitrate/nitrite were absent. In both lakes, however, the contents of organically bound P increased in the upper 0.5 cm layer during the summer stratification.

Busulwa and Bailey (2004) studied the physico-chemical environment of Rwenzori river, Uganda and observed that the conductivity values decrease as the rivers were effectively diluted and that with decrease in altitude it increases because of the increased runoff bringing more ions from the catchment.

Kalchev *et al*. (2004) studied ecological relations and temporal changes in the pelagial of the high mountain lakes in the Rila Mountains (Bulgaria). The findings indicated that the positive correlation exists between pH and SO_4^{2+} showing that sulphate ions mostly come from the weathering of rocks. It was further reported that the nutrient concentration and other dissolved chemical components were influenced by the soil coverage in their catchment areas.

Kumar *et al*. (2004), while studying water quality and macrophytes of Hokersar wetland and Manasbal lake reported that pH of both habitats remained in alkaline range while total phosphorus and orthophosphates showed a greater variations.

Kundangar and Adnan (2004) reviewed thirty years of ecological research on Dal lake and observed that considerable increase has occurred in silicate, nitrate, ammonical-nitrogen, total phosphorus, conductivity, sodium, potassium and total alkalinity of the lake.

Petaloti *et al.* (2004) worked on nutrient dynamics in Shallow Lakes of Northern Greece and noted that the physicochemical parameters determined in the lakes studied revealed a high temporal variation. The trophic state of the lakes ranged from mesotrophic to hypertrophic. The nutrient limiting factor varied among lakes suggesting either phosphorus-limitation conditions or mixed conditions changing from phosphorus- to nitrogen-limitation throughout the year.

Selig *et al.* (2004) investigated vertical gradient of nutrients in two dimictic lakes. It was observed that the entire hypolimnion was anoxic in both lakes during September and the redox potential decreased with increasing depth in the hypolimnia of both lakes.

Guildford *et al.* (2005) studied the phytoplankton nutrient status in Lake Erie. The study revealed that the phytoplankton in the western basin only infrequently showed signs of nutrient deficiency.

Marti and Imberger (2005), while studying on the dynamic behaviour of the benthic boundary layer in a thermally stratified lake, concluded that the vertical mixing between the epilimnion and hypolimnion affects the geochemical and biological processes.

Noges and Kangro (2005) carried out detailed study on primary production of phytoplankton in a strongly stratified temperate lake. The findings revealed that the decreased nutrient concentration in the epilimnion has supported the establishment of a ‘clear epilimnion state’ allowing light to penetrate into the nutrient-rich metalimnion, sustaining a high production of cyanobacteria and phototrophic sulphur bacteria.

Tonno *et al.* (2005) analyzed nitrogen dynamics in the steeply stratified, temperate Lake Verevi, Estonia. The study revealed that the nitrogen that accumulated in the hypolimnion was trapped in the non-mixed layer during most of the vegetation period causing a concentration of an order of magnitude higher than in the epilimnion.

Chimney *et al.* (2006) made a study on patterns of vertical stratification in a subtropical wetland in south Florida (USA). From the results of the study, it was concluded that the relative thermal resistance to mixing was used to infer the strength of thermal stratification. It was also observed that the open-water sites were nearly isothermal and had minimal thermal stratification, while vegetated sites were all thermally stratified to some degree.

Malmaeus and Rydin (2006) developed a model of the phosphorus dynamics for the profundal sediments of Lake Erken, Sweden. It was reported that 50% of the settled phosphorus is eventually buried, and the rest is released to the overlying water column and that the amount of phosphorus released is sensitive to temperature and O_2 concentration in the bottom water.

Timm *et al.* (2006) studied the macrozoobenthos in small lakes of Estonia. It was reported that the significant increase in abundance and biomass of *Chaoborus* may indicate decreased O_2 concentration in the hypolimnion, as well as an expansion of stratified areas to the shallower regions.

Larson *et al. (*2007), while analyzing thermal, chemical, and optical properties of Crater Lake Oregon, observed that the circulation of the deep lake occurs periodically in winter and spring when cold, near-surface waters sink to the lake bottom. It was pointed out that this process results in the upwelling of nutrients, especially nitrate-N, into the upper strata of the lake.

Zaccara *et al. (*2007) made a study on a northern Italian shallow lake as a case study for eutrophication control. The investigation concluded that the anoxic conditions in the hypolimnion of lakes leads to the release of phosphorus from sediments, which in turn drives the lake phosphorus-budget, and thus maintaining the lake in eutrophic status.

Katano *et al.* (2008) studied the abundance and composition of the summer phytoplankton community along a transect from the Barguzin River to the central basin of Lake Baikal. The study concluded that although the lake revealed thermal stratification but the thermocline developed at different depths at different places. Relatively high concentrations of nutrients were detected in the deeper parts of the euphotic zone.

Elci (2008), while studying effects of thermal stratification and mixing on reservoir water quality, revealed that during stratification dissolved oxygen concentrations drop well below the standard limit of 5 mg l^{-1} at the thermocline, leading to the development of anoxia.

Abd El-Monem (2008), while studying Impact of Summer Thermal Stratification Phytoplankton in Lake Nasser (Egypt), concluded that bands of stratification were affected with the inflow of River Nile. Net primary productivity was found to be irregular along the depth profile and superficial water had climax photosynthetic capacity and declined downward.

Boehrer *et al.* (2009) worked on the stratification features of deep caldera lakes in Japan and revealed that the incomplete mixing in these very deep lakes is referred to the depth dependence of the temperature of maximum density and salinity stratification and documented the inhomogeneous distribution of physico-chemical parameters over the water column.

Lehman (2009), while working on Lake Victoria, observed that the nutrient enrichment and climate warming contributed to deoxygenation of deep water habitats and promoted the rise of nuisance cyanobacteria and other changes in the lower food web. The lake behaved as a light-limited, nutrient-saturated ecosystem that is becoming as biologically sensitive to radiation balance as is its water budget.

Rueda and Schladow (2009), while studying mixing and stratification in lakes of varying horizontal length scales. The study depicted that the stratification can be transient or persistent, varying at time scales of hours to decades finally decaying to near vertical homogeneity as mixing mechanisms such as wind and convection outweigh the stabilizing inputs of surface heating.

Brum *et al.* (2010), while studying Morphological Characterization of Viruses in the Stratified Water Column of Alkaline, Hypersaline Mono Lake found that the physical and chemical stratification of Mono Lake resulted in differing assemblages of viruses in the three layers of the lake as determined by their morphological characteristics.

Özkundakci *et al.* (2010), while assessing the Effect of intensive catchment and in-lake restoration procedures on phosphorus concentrations in a eutrophic Lake Okaro observed that the lake was thermally stratified for an average of 8 months each year. The period of stratification was observed to be 1 month longer than that recorded in the 1970s. Whereas the water near the bottom of the lake became anoxic shortly after onset of stratification.

Yoshimizu *et al.* (2010) studied the vulnerability of a large monomictic lake (Lake Biwa) to warm winter event. The results depicted that during a warm winter, deep-water oxygenation was delayed by more than a month relative to normal years. The study also concluded that the Lake Biwa is sensitive to year-to-year variations in winter meteorological conditions.

Yu *et al. (*2010) investigated the chemical and thermal stratification in lakes and pointed out that the chemical stratification strength was largely determined by thermal stratification strength.

Romshoo and Muslim (2011), while assessing the nutrient load of lake- Manasbal through geospatial modeling, observed that the highest amount of nutrient loadings are observed during wet season in the month of March. Their 11-year simulations (1994–2004) showed that the main source areas of nutrient pollution in lake are agriculture lands and wastelands.

Sarah *et al*. (2011), while assessing variability of water quality in a groundwater-fed Manasbal lake of Kashmir Himalayas using linear geostatistics observed that the concentration of major ions in the water samples in winter was higher than in summer. The scatter diagrams suggested the dominance of alkaline earths over the alkali elements. The study also found that the lake water was controlled by rock–water interaction with carbonate lithology as a dominant source of the solutes.

Sturner (2012), while studying effect of temperature induced changes in mixing depth on nutrient concentrations in lakes revealed that during stratification, the partitioning of the concentrations of oxygen, inorganic nutrients (phosphorus and nitrogen) and iron (Fe) increased between the epi- and hypolimnion. The study also revealed that shallow lakes react rapidly to changing thermal regime and therefore nutrient recycling.

The above review clearly indicates that although numerous research studies have been conducted on lake ecosystems throughout world, the Kashmir Himalayan lakes have not received much attention and several gaps remained in our understanding of these important ecosystems.

CHAPTER – 3

STUDY AREA

The valley of Kashmir, located in the foothills of the Himalaya, abounds in numerous natural fresh water lakes that have come into existence as a result of various geological and geomorphological changes in the region. These lakes categorized into glacial, alpine and valley lakes based on their origin, altitudinal situation and nature of biota provide an excellent opportunity for studying the structure and functional process of an aquatic ecosystem system (Kaul 1977; Kaul *et al*., 1977; Khan 2006; Trisal 1985; Zutshi *et al*., 1972). Over the years, the unplanned urbanization, deforestation, soil erosion and reckless use of pesticides for horticulture and agriculture have resulted in heavy inflow of nutrients into these lakes from the catchment areas (Baddar and Romshoo, 2007). As a consequence, most of the lakes in the Kashmir valley are exhibiting eutrophication (Kaul 1979; Khan 2008).

Manasbal lake is the deepest (~12 m deep) of all the freshwater lakes fed by groundwater in Kashmir Valley (Lawrence 1895; Raina 1971). It is situated at an altitude of 1583 m amsl. It lies at $34^{o}14^{'}40^{''}$– $34^{o}15^{'}20^{''}$N and $74^{o}39^{'}00^{''}$ – $74^{o}41^{'}20^{''}$E and covers an area of about 280 ha of which 25 ha is marshy. The lake is surrounded by moderately high mountains on its eastern and southern sides. A few limestone quarries exist towards the eastern part. The northern bank of the lake comprises a raised land or Karewas. The oblong outline of Manasbal lake extends in a NE–SW direction with a maximum length and breadth of 3.5 and 1.5 km, respectively.

The volume of water has been estimated as 12.8×10^6 m^3 Yousuf (1992). The lake is also fed seasonally by an irrigational stream; Larkul, on the eastern side, which is operational only during summer season. The lake drains into the river Jhelum through a 1.6 km Nunnyar Nalla near Sumbal village. The lake serves as an important natural water reservoir for the local population and its water is used for drinking and agricultural purposes.

The climate of the study area is characterized by warm summers and cold winters. According to Bagnoulus and Meher- Homji, (1959) the climate of Kashmir falls under Sub-Mediterranean type with four seasons based on mean temperature and precipitation. The study area receives an average annual precipitation of about 650mm.

The topography of the catchment of Manasbal lake is undulating to flat with few steep slopes. Most of the streams are seasonal. The lake body has predominantly rural surroundings. The land use of the area is mainly agriculture and some of the main crops cultivated include rice and mustard. Large areas of barren, waste lands and horticulture are also found in the catchment area.

Although a few studies have been conducted on the thermal stratification of Manasbal lake, not much is known about the relationship between it and nutrient distribution across the strata. It was, therefore, decided to study the stratification in the lake from its initiation in March to the peak stratification time and find out its impact on the vertical distribution of nutrients, especially N & P.

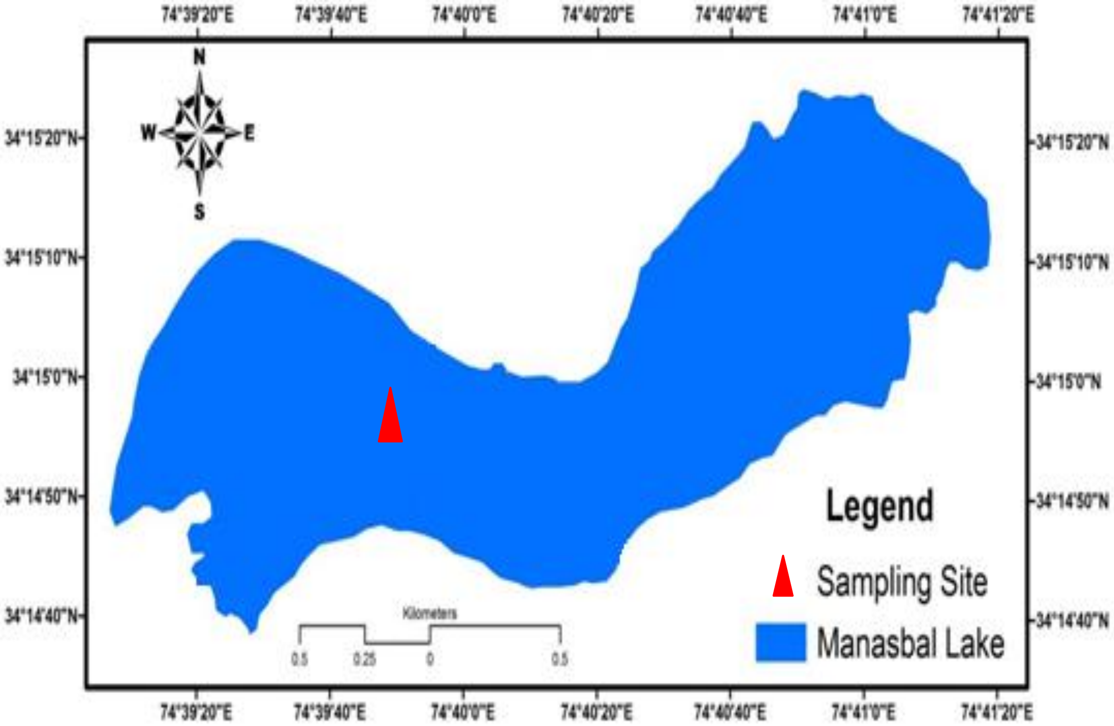

Figure I: Study Area Map

CHAPTER – 4

MATERIAL

&

METHODS

For the present investigation, the deepest point in the limnetic zone of Manasbal lake was selected (Fig. II.)

4.1. COLLECTION OF WATER SAMPLES

Since the lake was reported to be stratified for a large part of the year with distinct layers of epilimnion, metalimnion and hypolimnion, a well-planned sampling design was framed for the present study. Sampling was done fortnightly from March onwards and using a Ruttner Sampler (Fig. III), water samples were collected from various depths. The following parameters were determined:

1. Temperature of water after every meter.
2. pH, DO, electrical conductivity, total alkalinity, TDS after every meter
3. Other parameters after every 2 meters.

The air and water temperature, depth and transparency were determined on the spot, while other parameters were determined in the laboratory. The analysis was done as per standard methods given in CSIR (1974), Mackereth *et al*. (1978) and APHA 1998).

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Figure II: SAMPLING SITE

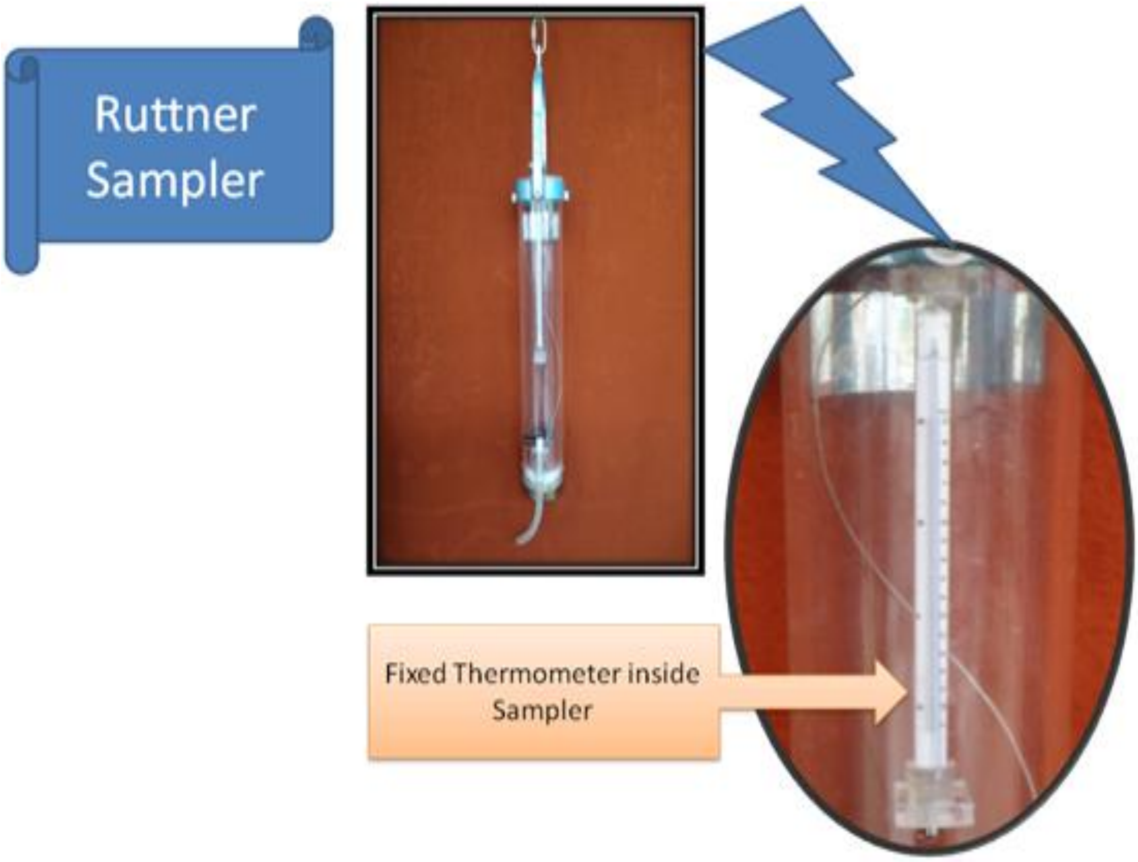

Figure III. Ruttner Sampler

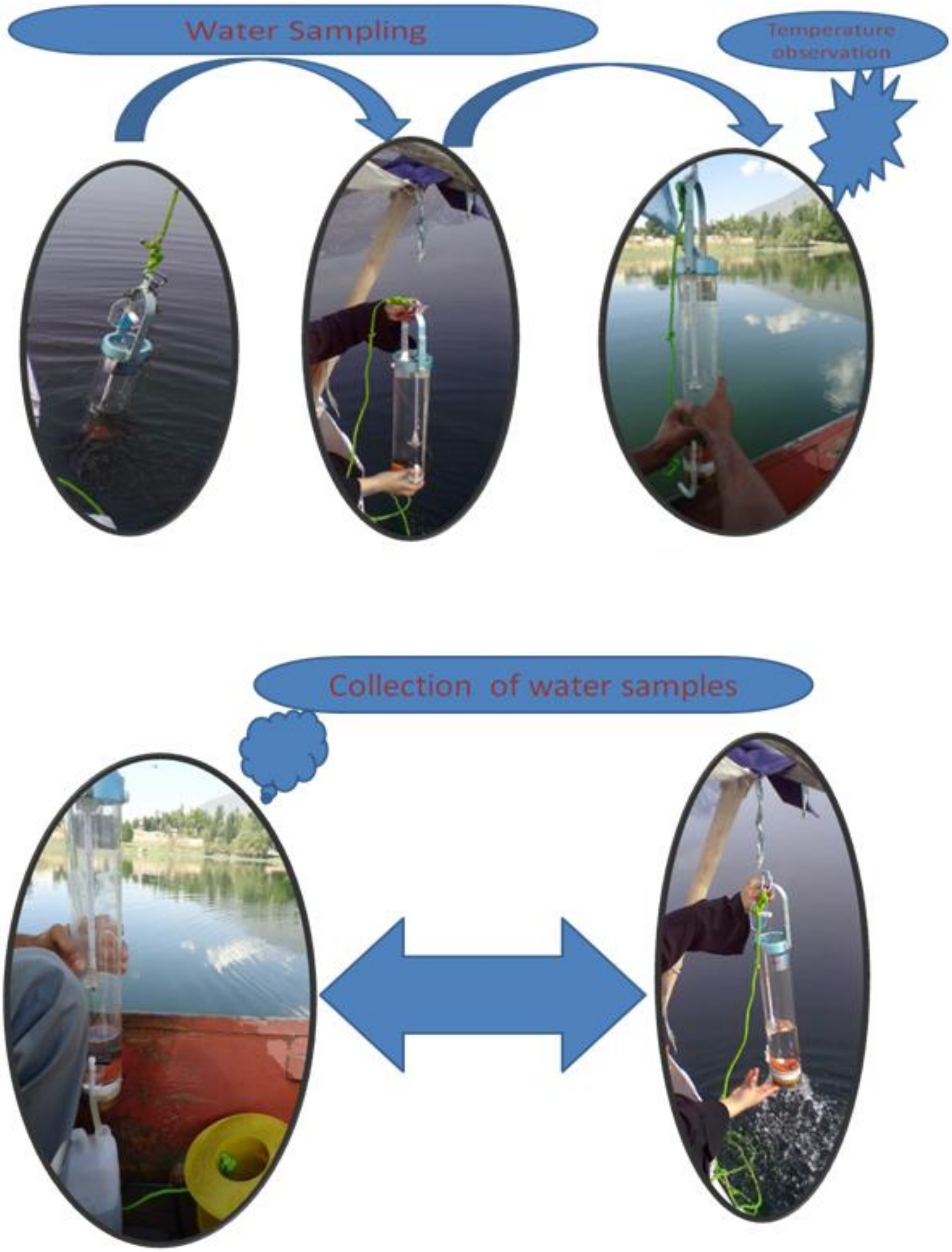

Figure IV. Collection of water samples

4.2. MEASUREMENT OF PHYSICO – CHEMICAL PARAMETERS

4.2.1. Temperature

The temperature of surface water and air was recorded by using graduated Celsius thermometer. The bulb of thermometer was dipped in water for at least two minutes for obtaining the water temperature. Air temperature was recorded in shade at the study site. The results were expressed in ^{o}C.

4.2.2. Depth

It was determined with a weighted graduated non – stretchable rope. The weight was lowered in water until it touched the bottom of lake and the depth was recorded.

4.2.3. Transparency

It was estimated by a 20cm diameter Secchi disc attached to a graduated non–stretchable rope. The disc was lowered in water and the average of the depth measurements at which it first disappeared and then reappeared upon raising slowly was taken as the transparency of the water. The measurements were taken from the shady side of the boat.

4.2.4. pH

The pH of water samples was measured by means of a Digital pH meter- 335, Systronics. Before measuring the pH of water samples, the pH meter was standardized with known buffer solutions of pH 4.7, 7.0, and 9.2.

4.2.5. Conductivity

The conductivity of water samples was measured with the help of a Digital-conductivity meter- 304, Systronics. The conductivity meter was calibrated before use with standard potassium chloride solution (0.01M).The results were expressed in µScm^{-1}.

4.2.6. Dissolved oxygen *(Iodometric Azide Modification Method*)

The water samples were collected in 300ml capacity BOD bottles fitted with tapered stoppers. The initial fixation was carried out in the field by adding 1ml each of $MnSO_4$ and alkali-iodide-azide reagent to the sample. After the brown precipitate had settled, the sample was acidified with 1ml Conc. H_2SO_4. Further analysis was undertaken in the laboratory 50ml of the fixed sample was taken and titrated against 0.025N sodium thiosulphate using starch as indicator till the first disappearance of blue colour. The dissolved oxygen concentrated was calculated from the given formula and the results were expressed in mg l^{-1}.

Dissolved Oxygen (mg l^{-1}) = $\frac{V_1 \text{ x N x e x } 1000}{V_2}$

V_1 = Volume of sodium thiosulphate used

V_2 = Volume of sample taken for titration

N = Normality of sodium thiosulphate

e = Equivalent weight of oxygen

4.2.7. Percent Oxygen Saturation

It was computed from the observed values of oxygen and temperature of the sample. The altitude of the study site was also considered for its calculation.

% Saturation of D.O = $\frac{\text{Observed D.O x } 100}{\text{Sx}}$

Sx = St x Cf

St = solubility of O_2 at the temperature t (of water sample)

Cf = altitudinal correction factor (1.21).

4.2.8. Free carbon dioxide (*Titrimetric Method*)

50ml of water sample was titrated against 0.02N NaOH, after addition of five drops of phenolphthalein (alcoholic indicator). The results were expressed as mg l^{-1}.

Free carbon-dioxide (mg l^{-1}) = $\frac{\text{Vol .of titrant used (ml) x N x 50,000}}{\text{Volume of samp le}}$

4.2.9. Total alkalinity (*Titrimetric Method)*

The method involves titrating 50ml aliquot of sample in an Erlenmeyer flask against 0.02N H_2SO_4 using phenolphthalein indicator in the first step and methyl orange in the second step; the changes in the color being pink to colorless in the first step and yellow to orange tint in the second step. The results were expressed in mg/l.

Total Alkalinity as $CaCO_3$ (mg l^{-1}) = $\frac{V_1 \text{ x N x } 50{,}000}{V_2}$

V_1 = Volume of titrant used.

V_2 = Volume of sample taken

N = Normality of H_2SO_4

4.2.10. Chloride (*Argentometric Method*)

50ml of sample was titrated against 0.0141N silver nitrate solution using potassium chromate as indicator till brick red colour endpoint was attained. Concentration in mg l^{-1} was determined by using the following formula.

Chloride (mg l^{-1}) = $\frac{V_1 \text{ x N x e x } 1000}{V_2}$

V_1 = Volume of titrant used (ml)

V_2 = Volume of sample taken for titration (ml)

N = Normality of silver nitrate solution

e = Equivalent weight of chlorine

4.2.11. Total hardness (*Complexometric Method*)

To 50ml of sample, 1ml of ammonia buffer solution and 5-10 drops of Eriochrome Black- T indicator was added and then titrated against 0.01N EDTA till wine red colour changes to blue. The concentration was determined by using the formula.

Total hardness as $CaCO_3$ (mg l^{-1}) $= \frac{V_1 \text{ x } B \text{ x } 1000}{V_2}$

V_1=volume of EDTA used (ml).

B = mg $CaCO_3$ equivalent to 1ml EDTA titrant

V_2 = volume of sample taken for titration (ml)

4.2.12. Calcium hardness (*Complexometric Method*)

To 50ml of sample 1ml of sodium-hydroxide and a pinch of murexide indicator was added and then titrated against 0.01N EDTA till purple color appeared. The concentration was determined by using the following formula.

Calcium hardness as $CaCO_3$ (mg l^{-1}) $= \frac{V_1 \text{ x } B \text{ x } 1000}{V_2}$

V_1 = volume of titrant used (ml).

B = mg $CaCO_3$ equivalent to 1ml EDTA titrant

V_2 = volume of sample taken for titration (ml).

4.2.13. Calcium content

Calcium (mg l^{-1}) $= \frac{V_1 \text{ x } 400 \text{ x } 1.05}{V_2}$

V_1 = volume of titrant used (ml).

V_2 = volume of sample taken for titration (ml).

4.2.14. Magnesium hardness

It was estimated as a difference between Total hardness and calcium hardness as $CaCO_3$ (APHA, 1998). The results were expressed in mg/l.

Magnesium (mg/l) = [Total hardness (as mg $CaCO_3$/L) – calcium hardness (as mg $CaCO_3$)]

4.2.15. Magnesium content

It was estimated as a difference between hardness and calcium as $CaCO_3$ (APHA, 1998). The results were expressed in mg/l.

Magnesium (mg/l) = [Total hardness (as mg $CaCO_3$/L) – calcium hardness (as mg $CaCO_3$)] x 0.243

4.2.16. Nitrate -nitrogen (*Sodium salicylate method, CSIR 1974*)

50ml of sample, after addition of 1ml of sodium salicylate was evaporated to dryness on water bath. The residue was treated with 1ml of concentrated sulphuric acid and after 5-10 minutes 6ml of distilled water and 7ml of 30% NaOH solution were added. After development of yellow colour, the intensity was measured at 410 nm with the help of a spectrophotometer- 106, Systronics. The nitrate- nitrogen content of the sample was deduced by comparing its absorbance with the standard curve which was obtained from the series of standard solutions using the stock solution of KNO_3 and the results were expressed in $\mu g\ l^{-1}$.

4.2.17. Ammonium -nitrogen (*Phenate Method, APHA 1998*)

To 25ml of water sample, 1ml Phenol, 1ml Sodium Nitropruside solution and 2.5ml of oxidizing solution were added. Then it was kept at room temperature for about 1 hour in subdued light, till the colour developed fully. The intensity of colour was measured at 640 nm with the help of a spectrophotometer- 106, Systronics. The ammonical-nitrogen content of the sample was deduced by comparing its absorbance with the standard curve which was obtained from the series of standard solutions using the stock solution of anhydrous NH_4Cl and the results were expressed in µg l^{-1}.

4.2.18. Nitrite –nitrogen (*Sulphanilamide Method)*

To 45ml of sample, 1ml of sulphanilamide solution was added. Then after 5 minutes 1ml N-1-napthyl ethylene diamine dihydrochloride reagent was added. After development of pink colour, volume was raised to 50ml with distilled water. The intensity of colour development was measured at 543 nm with the help of a spectrophotometer- 106, Systronics. The nitrate- nitrogen content of the sample was deduced by comparing its absorbance with the standard curve which was obtained from the series of standard solutions using the stock solution of $NaNO_2$ and the results were expressed in µg l^{-1}.

4.2.19. Orthophosphates (*Stannous chloride Method)*

To 50ml of sample, 2ml of ammonium molybdate and 5 drops of stannous chloride were added. The intensity of blue colour developed was measured after 10 minutes at 640 nm with the help of a spectrophotometer- 106, Systronics. The ortho-phosphate content of the sample was deduced by comparing its absorbance with the standard curve which was obtained from the series of standard solutions using the stock solution of anhydrous KH_2PO_4. The results were expressed in µg 1^{-1}.

4.2.20. Total Phosphate Phosphorus *(Stannous Chloride Method)*

The initial preparation of sample was done by double acid (nitric acid – sulphuric acid) digestion. To 25 ml aliquot of sample in an Erlenmeyer flask, 1ml of concentrated H_2SO_4 and 5ml concentrated HNO_3 were added and the mixture was digested to a volume of 1ml on a hot plate. On cooling, 20ml distilled water and 1 drop phenolphthalein indicator were added. The resultant solution was titrated against 1N NaOH solution until faint pink colour appeared. The volume was raised to 100ml by adding distilled water. In case the solution turned pink, strong acid solution was added dropwise to discharge the colour. After thorough mixing, 4ml ammonium molybdate reagent and 0.5ml stannous chloride were added. After a pause of 10 minutes, blue colour developed. The absorbance was measured at 690nm using a spectrophotometer- 106, Systronics. The total phosphate phosphorus content of the sample was deduced by comparing its absorbance with the standard curve which was obtained from the series of standard solutions using the stock solution of anhydrous KH_2PO_4 and the results were expressed in µg l^{-1}.

4.2.21. Total Dissolved solids (*Evaporation Method)*

50ml sample was filtered through a Whatman^{TM} #4 filter paper. Thereafter, the sample was dried in a tared evaporating dish to a constant weight at 180^{o}C in a drying oven for 1h. The sample was cooled in a dessicator and weighed on an analytical balance.

Total Dissolved solids mg/l = (A – B) x 1000/ ml sample

A = weight of dried residue + dish, mg

B = weight of dish, mg

CHAPTER – 5

RESULTS

5.1. TEMPERATURE

For the purpose of present study, the detailed thermal structure of the lake, the temperature at regular intervals of 1m depth was recorded fortnightly (Table 5.2). The different depths of water exhibited a characteristic fluctuation pattern of the temperature. During most period of the study, a regular temperature gradient existed between the surface and the deeper waters, the former always being at a higher temperature than the latter.

The fortnightly changes in temperature at different depths clearly indicated that the range of fluctuations narrowed from the surface towards the bottom; the upper layers had a wider range (up to 28.9^{o}C) than the bottom (up to8^{o}C). Depth profiles of water temperatures during summer are shown in Fig. 5.2(b). It shows that water column was thermally stratified. Its amplitude, a difference between surface and bottom water temperatures, had the widest range of about 19.2 °C on 5th August when water temperature decreased gradually downward from 28.4 to 9.2 °C. During the winter months, the entire water column had a uniform temperature, as shown in Fig. 5.2(d) with minor fluctuations in temperature from surface to bottom in the month of December ranging from (9 ^{o}C – 9.4 ^{o}C) with a temperature difference of 0.4^{o} C. The lowest temperature of 4.5 ^{o}C at all depths was recorded on 1st February.

The changes in the surface water temperature were directly related to the sunshine and hence followed closely the changes in the atmospheric temperature. In July, when the highest air temperature was 32^{o}C, the temperature of the surface water was recorded as 28.9^{o}C. From August onwards, the atmospheric temperature dropped gradually and the water temperature also experienced a gradual fall. Since most of the solar energy was utilized by the upper layers and very little heat passed to the deeper ones, variations in the temperature of various depths was observed from March onwards. The stagnation period of the lake, which started in March, continued in the following months, resulting in the temperature gradient between the surface and bottom. With the formation of thermocline, temperature gradient became more pronounced in the water column. On 15th March, the thermocline was noticed between 2m and 3m depth with a fall of 2.5°C. The epilimnion, was thus very thin represented by first two metres only while the hypolimnion extended from 3m downwards. The temperature record of 7th April, however, showed the epilimnion to have extended upto 3m depth, the thermocline was between 3m and 6m and the hypolimnion extended from 6m downwards and on 23rd April, the epilimnion was between 0m and 2m, the thermocline between 2m and 6m and the hypolimnion extended below from 6m depth (Fig. 5.2a). The data from 2nd June to 5th August shows that the thermocline started to expand from 5m depth to 10m depth, thus restricted epilminion upto 4m depth, while the hypolimnion extended from 8m downwards and was greatly reduced, being restricted to 10m downwards on 5th August (Fig. 5.2b). In September, the thermocline region slightly decreased being limited to the depth between 7m and 9m and 8m and 11m, and thus restricted the hypolimnion below 10m and 11m depth on 8th September and 22nd September respectively. On 12th October, the epilimnion was found to have increased upto a depth of 7m depth, expanding epilimnion upto 8m deep, represented the maximum thickness of epilimnion, and thus reducing the thermocline zone for one metre between 8m and 9m, but the hypolimnion slightly increased, being limited to the region from 10m downwards (Fig. 5.2c). Thereafter, in winter the thermocline completely disappeared, resulting in the total circulation of water from surface to bottom.

5.2. DEPTH

The different values of water depth recorded at central site during the study period are given in Table 5.3.The water depth varied from 11m – 12.9m, and highest values were obtained during summer (Fig. 5.3a).

5.3. TRANSPARENCY

The depth to which light penetrated as determined by Secchi disc, fluctuated throughout the study period. In the limnetic zone, which is characterised by the paucity of macrophytes, by and large the water was clear and light penetration was observed even upto the depth of 4.5m. The transparency varied from 2m – 4.5m during the study period (Table 5.3). The lower values of light penetration were observed in the month of March and February, while the deeper light penetration records were obtained in June, July and December (Fig. 5.3b).

5.4. pH

The different values of recorded pH at the central site during the study period are given in Table 5.4. The pH varied from 6.9 (at bottom on 19th July and 8th September) to 8.9 (at surface on 2nd June, 19th July and 5th August). Maximum value of pH was recorded in surface waters and minimum in bottom waters. The surface waters were more alkaline upto the depth of 7m than the deeper ones till October and the pH remained above 8. Contrary to this, pH of the deeper strata from 8m downwards was almost always below 8 and at times showed a tendency towards neutrality. Slightly acidic pH was recorded below 11m depth for most part of the year (Fig. 5.4a – 5.4c).

During winter months (December and February), when the water was in circulation, the pH showed very little variation from surface to bottom ranging from 7.1 to 7.9 (Fig. 5.4d), whereas during the stagnation period the pH showed more vertical difference resulting in the formation of a pH gradient with depth .

5.5. CONDUCTIVITY

Conductivity is an important physical quality parameter, which explains the ionic status of all waters and its range of fluctuations during the study period is given in Table 5.5. A wide fluctuation was recorded in conductivity at all depths from surface to bottom throughout study**.** The conductivity values ranged from 160µScm^{-1} at surface on 4th July to 350µScm^{-1} at bottom on 1st February. Minimum values of conductivity were recorded in upper layers of water and maximum in deeper waters. Therefore the conductivity values increased from surface to bottom (Fig. 5.5a – 5.5d). Higher values of conductivity 350 µScm^{-1} and 370µScm^{-1} were observed in the months of August and September in the bottom waters during the stagnation period. Relatively higher values of conductivity were observed in February throughout the water column when the circulation was complete.

5.6. DISSOLVED OXYGEN

Oxygen concentration depicted significant variation with regard to depth. Depth profiles of DO concentration in water (Table 5.6) depicted that maximum concentration was 9 mg/l O_2 at surface on 1st February, while the period of lowest concentration at different depths varied. During stagnation of the lake, Oxygen depletion occured in deeper layers until it was deoxygenated in the hypolimnion layer with a concentration of 0.5 mg O_2 l^{-1} at 11m depth which finally resulted in its complete disappearance from this zone. O_2 concentration was considerably low in the water from 7m downwards towards the bottom layers of 12 and 13m where it was completely anoxic throughout the study period. In bottom layers, O_2 was reintroduced only when the water circulated completely and the presence of gas was evident in bottom layers on 1st February (Fig. 5.6I d).

The continuation of thermocline resulted in the anoxic conditions of water from 8m depth on 8th September (Fig. 5.6I c). On 22nd September, the thermocline got restricted between the depths 8m and 11m and as a consequence oxygen reappeared after depletion. Below this depth the anoxic layer continued to exist till December. Following the narrowness of the boundaries of thermocline and towards circulation, the O_2 concentration of epilimnion fell, narrowing the appreciable differences of O_2 content in the epilimnetic region. As per the data, the thermocline got destratified on 19th December. However, anoxic conditions of water still prevailed from 10m depth downwards, which indicated only partial mixing of water column. The presence of DO throughout the whole column column at all depths on 1st February suggests complete circulation of water.

The difference in oxygen content between the maximum and minimum values in water column, which can be defined as oxycline amplitude varied during study, as illustrated in Fig. 5.6I (a – d). The widest range of oxycline amplitude was about 8 mg/l O_2 on 2nd June.

5.7. PERCENT OXYGEN SATURATION

Only slight vertical variations were recorded in saturation level of DO in the upper layers whereas remarkable declining trend was recorded in the deeper layers (Table 5.7). During stagnation, the maximum difference of 128.65% in O_2 saturation was recorded between surface and 12m depth on 17th June (Fig. 5.7II b), whereas it was only 65.66% on 1st February during circulation of lake (Fig. 5.7II d). The whole water column was undersaturated on 15th March and 7th April. The first meter of the water column showed supersaturation on 23rd April, while on 2nd June supersaturation existed upto 3m depth of water (Fig.5.7I). Thereafter, the whole water column was again undersaturated with oxygen throughout the study. The undersaturated condition improved a little in the surface water from July to September but it declined again in the months of October and December. The level of saturation increased again on 1st February. Below the depth of 4m the entire water column remained in an undersaturated condition throughout study period.

Figure IV: Effect of stratification on Dissolved Oxygen

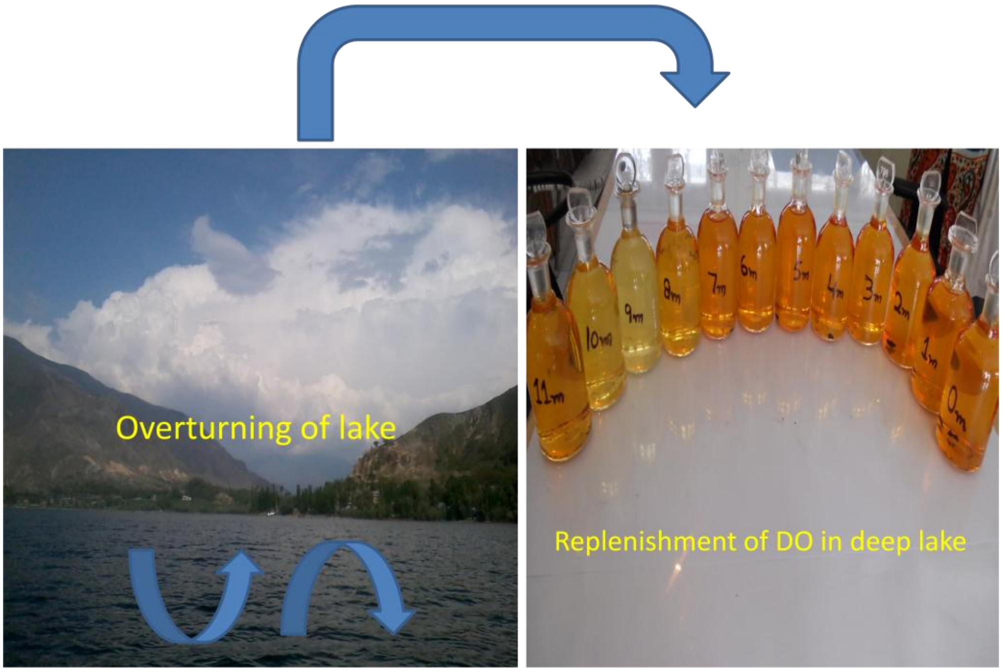

Figure V: Replenishment of Dissolved Oxygen in deeper layers

5.8. TOTAL ALKALINITY

Alkalinity (the acid consuming capacity) results from the weak acids and anions which can accept and neutralize protons and is imparted by the presence of HCO_3^{-2} and CO_3^{-2}. The bottom water had higher alkalinity values as compared to surface water in the entire period of study (Table 5.8). During the stagnation period, the range of variations from surface to bottom in total alkalinity were very large as was evident from the data obtained from April to September and attained maximum of 82mg/l on 4th July (Fig. 5.8c) . During the circulation period, in the month of December and February, the range of variation from surface to deeper layers gradually decreased and attained the minimum value of 18mg/l on 1st February. Minimum values of total alkalinity in surface waters were obtained from June to September and the highest values in surface waters were obtained in the month of December and February.

5.9. FREE CARBON DIOXIDE

The free CO_2 regime from surface to bottom waters at different depths during the entire study is given in Table 5.9. The gas showed a distinct vertical gradient, being more in deeper layers of water than in upper layers. It was absent in the epilimnion from 2nd June to 5th August and the data also shows its absence in the first two metres of thermocline region on 2nd and 17th June (Fig. 5.9b). With the establishment of well- developed thermocline on 23rd April, the free CO_2 in the epilimnion and thermocline showed a decrease, while it increased in the hypolimnion (Fig. 5.9a).From 6m downward, the bottom depths were never devoid of gas and showed abundant quantities.

On 22nd September, the gas reappeared in small quantities in the upper layers. With the lowering of the upper limit of thermocline on 22nd September and 12th October and the corresponding increase of epilimnion, the free CO_2 was fairly distributed upto a depth of 6m (Fig. 5.9c). A large quantity of gas was reported in the hypolimnion and a marked difference between 6m and bottom layers. During the circulation in winter months (December and January) the availability of free CO_2 showed a uniform pattern in the whole water column but with higher values at bottom on 19th December (Fig. 5.9d).

5.10. CHLORIDE

Chloride occurs naturally in all types of water. In natural freshwater, however, its concentration remains quite low and is generally less than that of sulphates and bicarbonates. Chloride content at various depths is given in Table 5.10. The vertical distribution of chloride content showed increasing trend from surface to bottom waters but did not show any striking variations from surface to bottom. The content in the three zones generally fluctuated in the same range of 4-8 mg/l throughout the study period. The maximum values were detected during the months of September, October, December and February, as illustrated in Fig. 5.10 (c and d) and the minimum values of chloride content were obtained in March and April (Fig. 5.10a).

5.11. TOTAL HARDNESS

Principal cations imparting hardness are calcium and magnesium. However, other cations such as strontium, iron and manganese also contribute to it. The anions responsible for hardness are mainly bicarbonate, carbonate, sulphate, chloride, nitrate and silicates, etc. The detailed data on the hardness, recorded during the period of study in the

Lake, are given in Table 5.11. In general, the hardness varied from 64 mg l^{-1} - 206 mg l^{-1} during the entire study. The vertical distribution of total hardness showed a regular gradient from surface downwards. The deeper layers always showed a higher concentration of hardness. The lowest value of 64mg/l was observed on 4th July (Fig. 5.11b) in surface layer, while the highest value of 206mg/l was obtained on 8th September at bottom (Fig. 5.11c).

The total hardness variations between the various depths varied greatly recording a difference of 50- 108mg/l during the stagnation period. During the period of winter circulation, the hardness was more or less uniform at all depths and the fluctuation ranged between 38 - 55mg/l in the months of December and February (Fig. 5.11d).

From early stratification period in April, the variation in hardness content between surface and bottom waters started to increase and it was maximum in September due to increase in hardness of water in hypolimnion. Minimum values of hardness were obtained in the epilimnetic water and upper metalimnetic region on 17th June, 4th and 19th July and in the epilimnetic region on 5th August (Fig. 5.11b) and then onwards in the surface waters only.

5.12. CALCIUM HARDNESS

Calcium hardness at various depths varied from 54 mg/l- 138mg/l (Table 5.12). There was a rapid increase of calcium hardness at different depths during stratification period. Higher values of calcium hardness were obtained in hypolimnion throughout the study period, being much higher in March, April, September and October. Minimum values of calcium hardness were obtained in the epilimnetic region from 2nd June to 8th September (Fig.5.12 a – 5.12c). During winter circulation on 1st

February uniform distribution of calcium hardness was observed (Fig. 5.12d).

5.13. CALCIUM ION

Calcium is one of the most abundant substances in natural waters. The quantity of Ca in natural water generally varies from 10mg/l to 100 mg/l depending on the type of rocks (Trivedy and Goel, 1986). Ca content at different depths varied from 21 – 55 mg l^{-1} (Table 5.13). There was a slight increase of calcium content at different depths during stagnation. Highest calcium content was found in hypolimnion and lowest in the epilimnetic region.

5.14. MAGNESIUM HARDNESS

There is less contribution of magnesium hardness to the total hardness as compared to the calcium hardness (Table 5.14) and the magnesium hardness increased with depth from surface to bottom waters and maximum value was encountered in hypolimnion during stagnation, being 81mg/l on 8th September (Fig. 5.14c).The minimum value of 10mg/l was reported on 4th July in surface water (Fig. 5.14b).

5.15. MAGNESIUM ION

Mg content at different depths is presented in Table 5.15. The highest quantity observed was 21mg/l at 12m on 15th March and the lowest quantity (3mg/l) in the surface layer on 4th July (Fig. 5.15a and 5.15b). In general, there was an increase in magnesium content with depth.

5.16. ORTHOPHOSPHATE

The orthophosphates varied in its distribution from surface to bottom and the overall range of variations was from 0- 133µg/l, Table 5.16. The pattern of fluctuations did not exhibit any regular gradient from surface to bottom. On 15th March, the orthophosphate phosphorus was maximum in the deeper layers of hypolimnion and minimum concentrations in the epilimnetic region. In the month of April and June, minimum concentrations were observed in the epilimnetic and thermocline region except at 4m depth on 7th April and at 8m depth on 17th June and maximum concentrations were in the hypolimnetic region of water. In July, minimum concentrations in the epilimnion, were followed by an abrupt increase in concentration at 8m depth in the thermocline region and a sudden fall at 10m depth. The maximum concentrations were found in the bottom layers of hypolimnion. On 5th August and 8th September the concentration of orthophosphate was found to be more in epilimnion than thermocline and the concentration further increased in hypolimnion. On 22nd September and 12th October, there was maximum concentration in hypolimnion than epilimnion and thermocline. On 19th December and 1st February, concentrations were still maximum in bottom layers and minimum in upper layers of water (Fig. 5.16d).

5.17. TOTAL PHOSPHORUS

The deep water were observed to be rich in total phosphorus content. All depths from surface to bottom showed variation in distribution of phosphorus and the overall range of variations was from 38- 852 µg/l (Table 5.17). The fluctuation in concentration from surface to bottom increased in the months of June, July and August (Fig. 5.17b). The minimum values were reported at 4m and 6m depth on 15th March and at 0m and 2m depth on 7th April during stagnation (Fig. 5.17a). During circulation, the minimum values were reported at 10m and 12m depth on 19th December and at 10m depth on 1st February and uniform distribution were reported from surface to 8m depth on the said date (Fig. 5.17d). Maximum concentration of 852 µg/l were recorded at 13m depth on 17th June. The pattern of fluctuation from surface to bottom did not exhibit any regular gradient except February.

5.18. AMMONIUM - NITROGEN

Ammonium- nitrogen content from surface to bottom varied between 9 µg/l – 986 µg/l (Table 5.18). The maximum ammonium-nitrogen concentration was recorded in bottom waters during summer stratification period. The concentration was found to be much higher in hypolimnion as compared to epilimnion and thermocline. The fluctuation in the concentration of anion at the various depths from surface to bottom was higher during stagnation of lake, while during circulation the fluctuation at various depths decreased. On 19th December, a sharp increase in all upper three depths was observed (Fig. 5.18d). During circulation on 1st February, the concentration of NH_4-N was low at all depths, while the stagnation period recorded maximum concentration almost always in bottom layers (Fig. 5.18a – 5.18d).

5.19. NITRATE - NITROGEN

The Nitrate status of water from surface to bottom is given in Table 5.19. Nitrate- nitrogen from surface to bottom varied from total absence to 988µg/l. The fluctuation at various depths was not regular, being different at different depths and the overall concentration of nitrate-nitrogen was observed to increase from surface to bottom with depth. The minimum values were recorded at upper three depths (0m, 2m and

4m) from 23rd April to 12th October except 4th July, as the concentration was observed to decrease on the said date. During circulation, the concentration was minimum at all depths on 19th December. The content was slightly higher on 1st February (Fig. 5.19d).

5.20. NITRITE- NITROGEN

The nitrite- N content at various depths from surface to bottom is given in Table 5.20. The concentration varied from total absence to 66µg/l. During stagnation period, the deeper layers were richer in nitrite- N than upper ones and the variation between surface to bottom was more pronounced in this period than circulation (Fig. 5.20a – 5.20c). During circulation on 1st February, the minimum values were obtained at all depths (Fig. 5.20d).

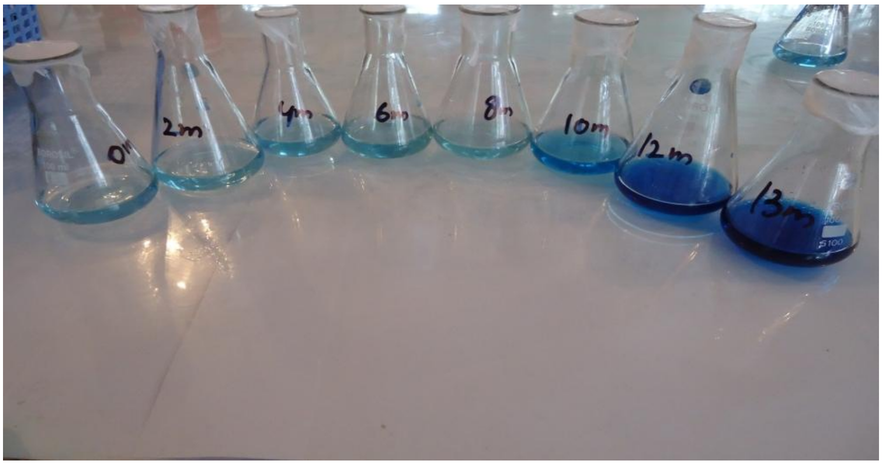

Figure VI: Variation in Ammonium-nitrogen (µgl^{-1}) at different depths in Manasbal lake

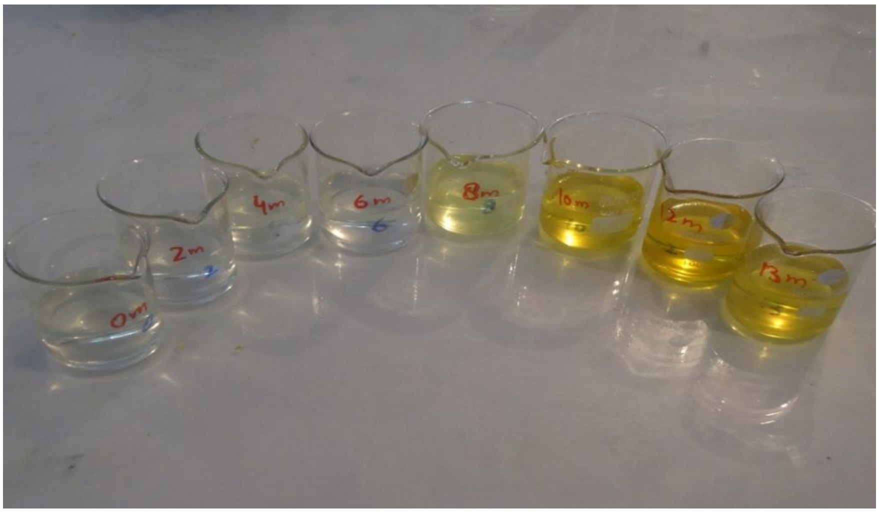

Figure VII: Variation in Nitrate-nitrogen (µgl^{-1}) at different depths in Manasbal lake

Figure VIII: Variation in Nitrite-nitrogen (µgl^{-1}) at different depths in Manasbal lake

5.21. TDS

The details of TDS of water at different depths from surface to bottom during the study period are given in Table 5.21**.** The TDS values ranged from 96mg/l on 4th July in surface layer to 220mg/l on 5th August and 8th September in hypolimnetic region. The higher values of TDS were observed in the hypolimnetic region and the lower values were found in epilimnetic region throughout the study period. The range of variation from surface to bottom layers increased during stratification. The higher TDS values were observed on 1st February at all depths throughout the entire water column (Fig. 5.21d).

Table 5.1: Variation in Air temperature (ºC) at different depths at Manasbal lake

Variable	MONTH												
	15th Mar	7th Apr	23rd Apr	2nd Jun	17th Jun	4th Jul	19th Jul	5th Aug	8th Sept	22nd Sept	12th Oct	19th Dec	1st Feb
Air temperature (ºC)	20	13.6	21.6	24	25	32	32	31	30	30.1	29	9	6

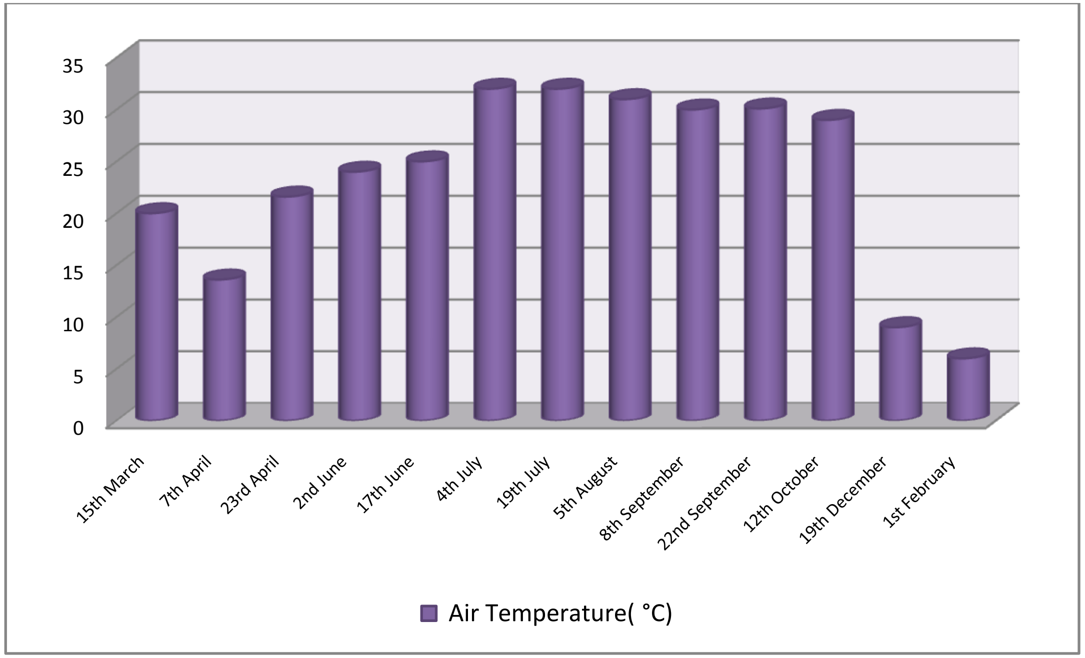

Figure 5.1: Variation in Air Temperature (ºC) on different dates in Manasbal lake

Table 5.2: Variation in Water Temperature (°C) at different depths in Manasbal lake

Depth (m)	MONTH												
	15th Mar	7th Apr	23rd Apr	2nd June	17th June	4th July	19th July	5th Aug	8th Sept	22nd Sept	12th Oct	19th Dec	1st Feb
0 m	16	13.4	19.9	25	27.2	27.2	28.9	28.4	27.2	24.3	17.3	9.4	4.5
1m	16	13.3	19.8	24.9	27.1	27	28.6	28.4	26.5	23.8	16.9	9.2	4.5
2m	15.5	13.2	19.1	24.9	27	26.5	28.2	28.4	26.2	23.5	16.9	9.2	4.5
3m	13	12.8	17.6	24	27	26.4	27.2	28	26.2	23.3	16.9	9.2	4.5
4m	13	12.7	17.5	23	26.2	25.8	26.2	27.2	26.1	23.1	16.8	9.2	4.5
5m	12.5	11.6	14	22	25.2	25.2	25	26.8	25.3	23	16.7	9.2	4.5
6m	12.4	10.4	12	19	23.8	22.2	22.2	25.3	25	23	16.7	9.2	4.5
7m	12.2	9.8	11.4	17	22.2	21.4	20	23.3	25	22.9	16.7	9.2	4.5
8m	11.7	9.4	10	17	17.8	18.2	18.3	22.3	19	22.2	15.7	9.1	4.5
9m	11.7	9.2	9.1	14	13	15.2	15.3	19.5	12.2	20.1	13	9	4.5
10m	11.7	8.9	9	13.9	12.7	14	14.2	12.5	10.9	19.1	13	9	4.5
11m	11.7	7.5	9	13	12.7	13.9	14.4	11.6	10.4	13	13	9	4.5
12m	11.7	7.5	8	11	12	13.8	14.4	11.2	9.3	12	12.7	9	
13m		7.4	8	9	11.6	13.7	14	9.2	9	10.1	12.5		

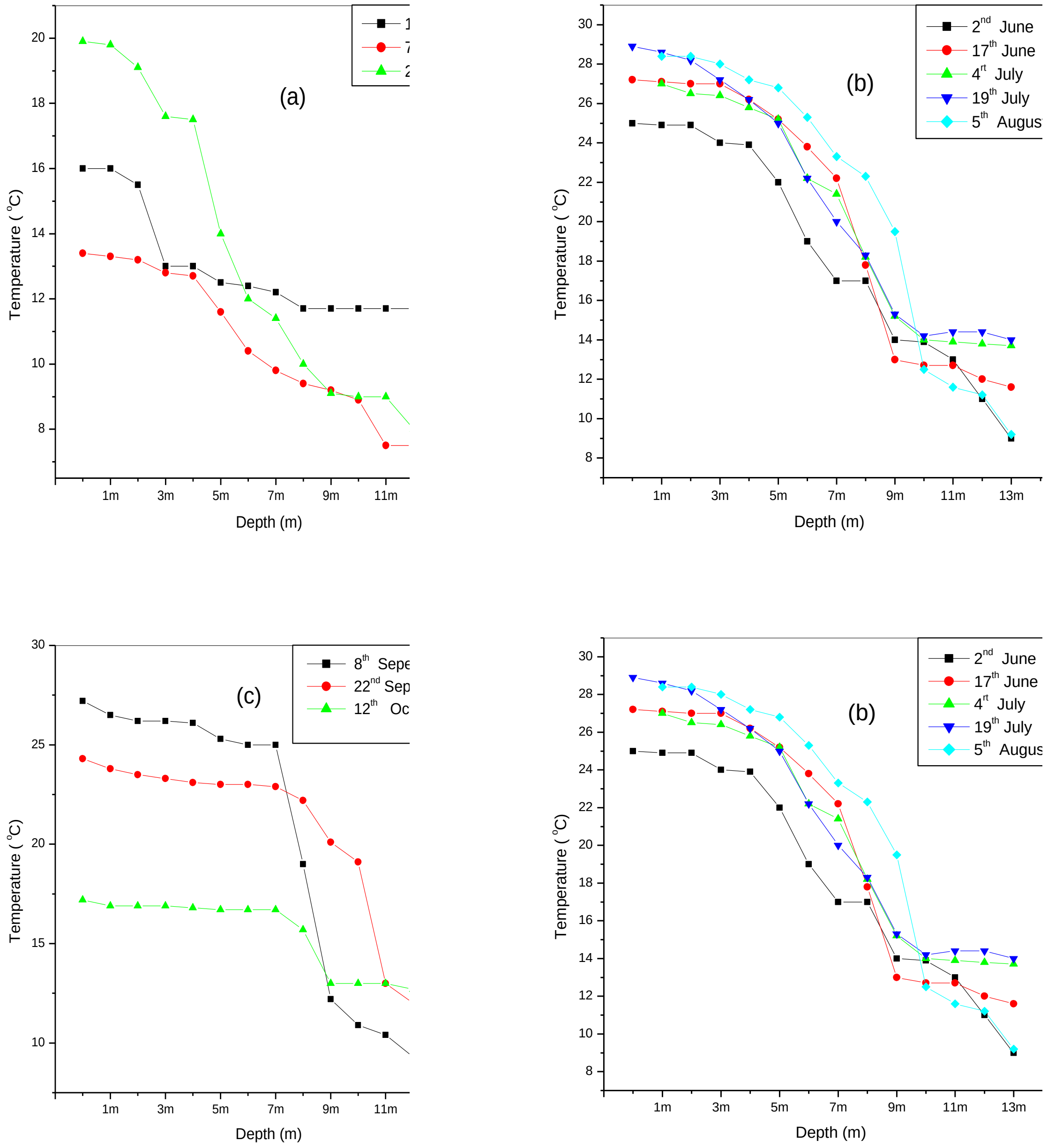

Figure 5.2: Variation in Water Temperature (^{o}C) at different depths in Manasbal lake during stratification and circulation

Table 5.3: Variation in Depth and Transparency (m) at different depths in Manasbal lake

Variables	MONTH												
	15th Mar	**7th Apr**	**23rd Apr**	**2nd June**	**17th June**	**4th July**	**19th July**	**5th Aug**	**8th Sept**	**22nd Sept**	**12th Oct**	**19th Dec**	**1st Feb**
Depth (m)	12	12.8	12.8	12.9	12.7	12.3	12.4	12.3	12.5	12.6	12.5	11.6	11
Transparency (m)	2	2.75	3.2	4.2	4.2	4.5	4.3	3.3	3.3	3.2	3.1	3	2.95

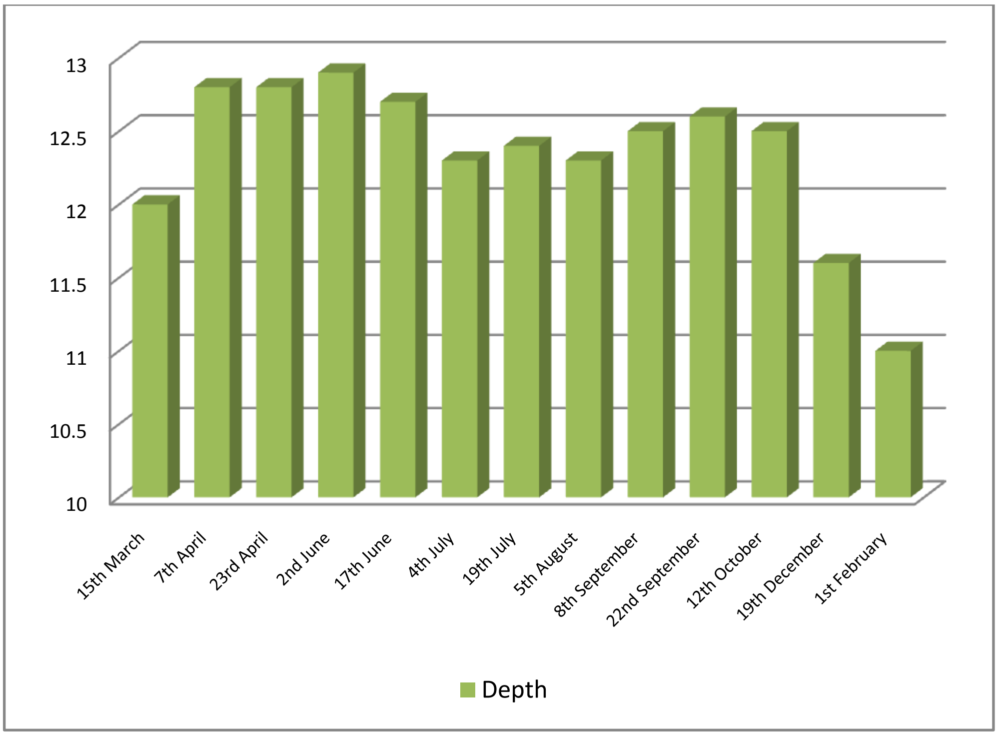

Figure 5.3(a): Variation in Depth (m) on different dates in Manasbal lake

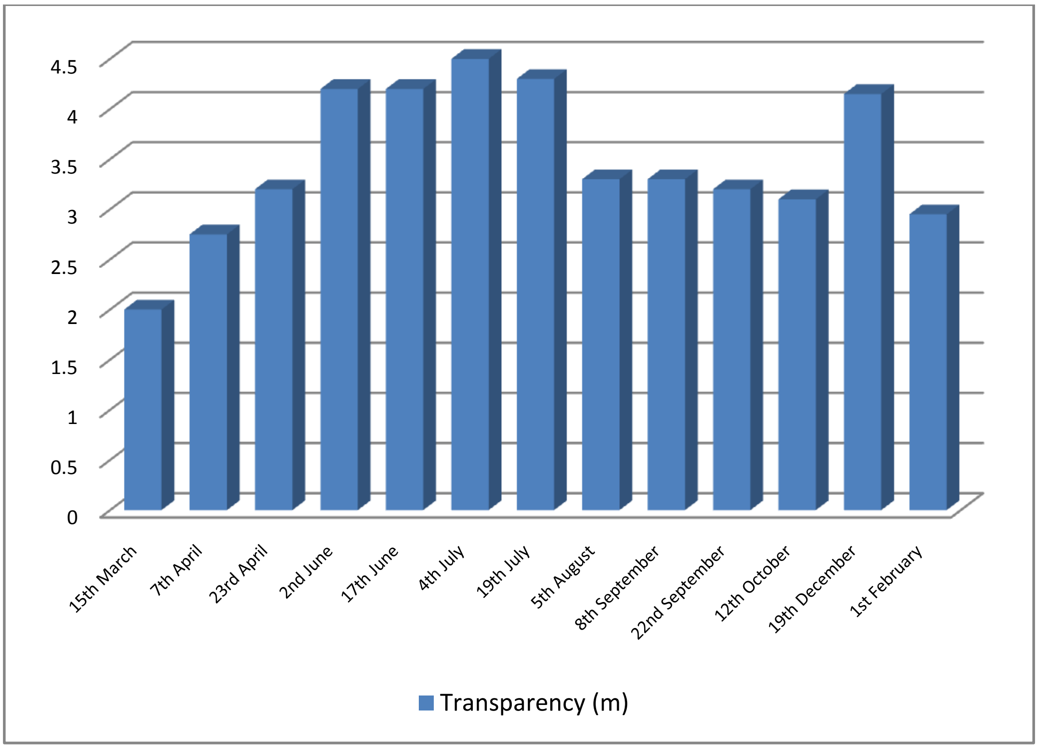

Figure 5.3(b): Variation in Transparency (m) on different dates in Manasbal lake

Table 5.4: Variation in pH at different depths in Manasbal lake

Depth (m)	**MONTH**												
	15th Mar	**7th Apr**	**23rd Apr**	**2nd June**	**17th June**	**4th July**	**19th July**	**5th Aug**	**8th Sept**	**22nd Sept**	**12th Oct**	**19th Dec**	**1st Feb**
0 m	8.84	8.4	8.6	8.9	8.2	8.6	8.9	8.9	8.6	8.1	8.1	7.7	7.9
1m	8.76	8.4	8.7	8.8	8.2	8.6	8.6	8.7	8.5	8.1	8.1	7.7	7.9
2m	8.76	8.3	8.5	8.8	8.2	8.6	8.6	8.7	8.5	8.1	8	7.4	7.9
3m	8.74	8.3	8.5	8.7	8.2	8.5	8.6	8.7	8.4	8.1	8	7.4	7.6
4m	8.67	8.2	8.1	8.7	8.2	8.5	8.4	8.4	8.3	8.1	8	7.4	7.6
5m	8.54	8.2	8	8.6	8.2	8.2	8.2	8.2	8.3	8.1	8	7.5	7.6
6m	8.46	8.2	8	8.6	8.2	8.2	8.1	8.1	8.1	8.1	8	7.5	7.6
7m	8.44	8.1	8	8.6	8.2	8	8	8	8	8	8	7.3	7.5
8m	8.39	7.9	7.8	7.8	7.3	7.9	7.9	7.9	7.7	7.6	7.5	7.3	7.5
9m	7.72	7.9	7.7	7.7	7.3	7.8	7.9	7.8	7.7	7.5	7.5	7.2	7.4
10m	7.6	7.7	7.7	7.7	7.3	7.7	7.6	7.6	7.6	7.5	7.4	7.2	7.4
11m	7.58	7.7	7.7	7.7	7.3	7.5	7.6	7.6	7.5	7.4	7.4	7.1	7.3
12m	6.7	6.8	6.4	6.7	6.8	6.7	6.9	6.6	6.9	6.9	6.8	7.1	
13m		6.7	6.3	6.4	6.8	6.7	6.9	6.5	6.9	6.8	6.8		

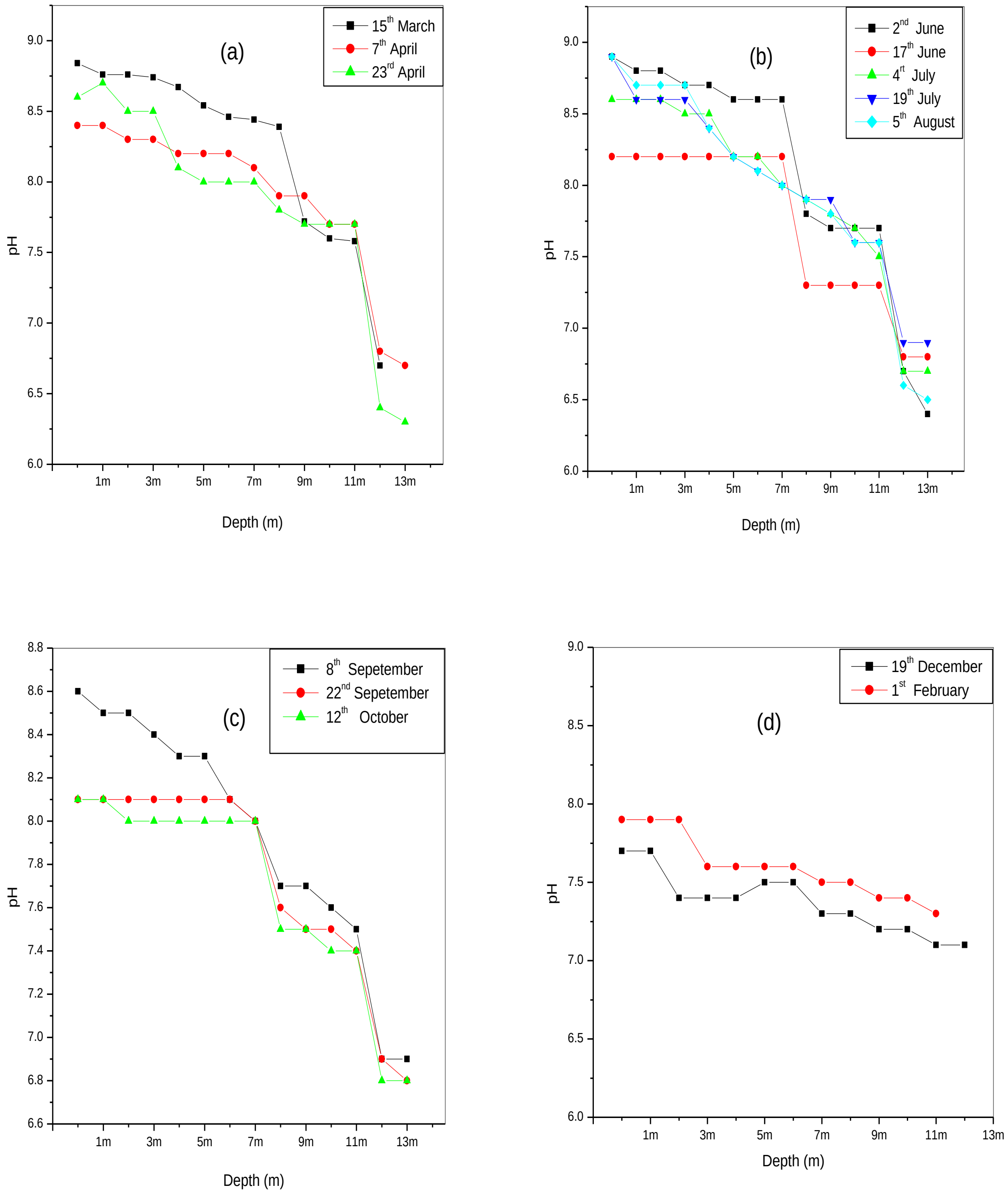

Figure 5.4: **Variation in pH at different depths in Manasbal lake during stratification and circulation**

Table 5.5: Variation in Conductivity (μS cm^{-1}) at different depths in Manasbal lake

Depth (m)	**MONTH**												
	15th Mar	**7th Apr**	**23rd Apr**	**2nd June**	**17th June**	**4th July**	**19th July**	**5th Aug**	**8th Sept**	**22nd Sept**	**12th Oct**	**19th Dec**	**1st Feb**
0 m	210	170	200	180	170	160	180	200	200	220	200	190	280
1m	220	200	200	180	180	170	190	210	200	220	210	200	280
2m	220	220	200	180	180	180	190	210	200	220	210	200	280
3m	220	220	210	180	180	180	190	220	200	220	220	200	290
4m	230	220	210	180	180	180	200	220	210	220	230	200	290
5m	230	240	240	210	190	190	220	260	210	220	230	200	310
6m	230	260	250	220	230	220	220	260	240	230	230	200	310
7m	230	260	250	230	240	230	230	280	260	240	240	200	310
8m	230	260	250	240	280	230	230	280	280	250	240	200	310
9m	230	260	260	240	280	240	240	290	330	250	250	200	320
10m	240	270	270	240	280	250	250	320	360	270	260	210	320
11m	240	270	270	250	280	250	270	350	360	310	300	220	350
12m	250	280	270	250	290	250	270	350	370	330	310	290	
13m		280	270	280	290	260	300	370	370	350	340		

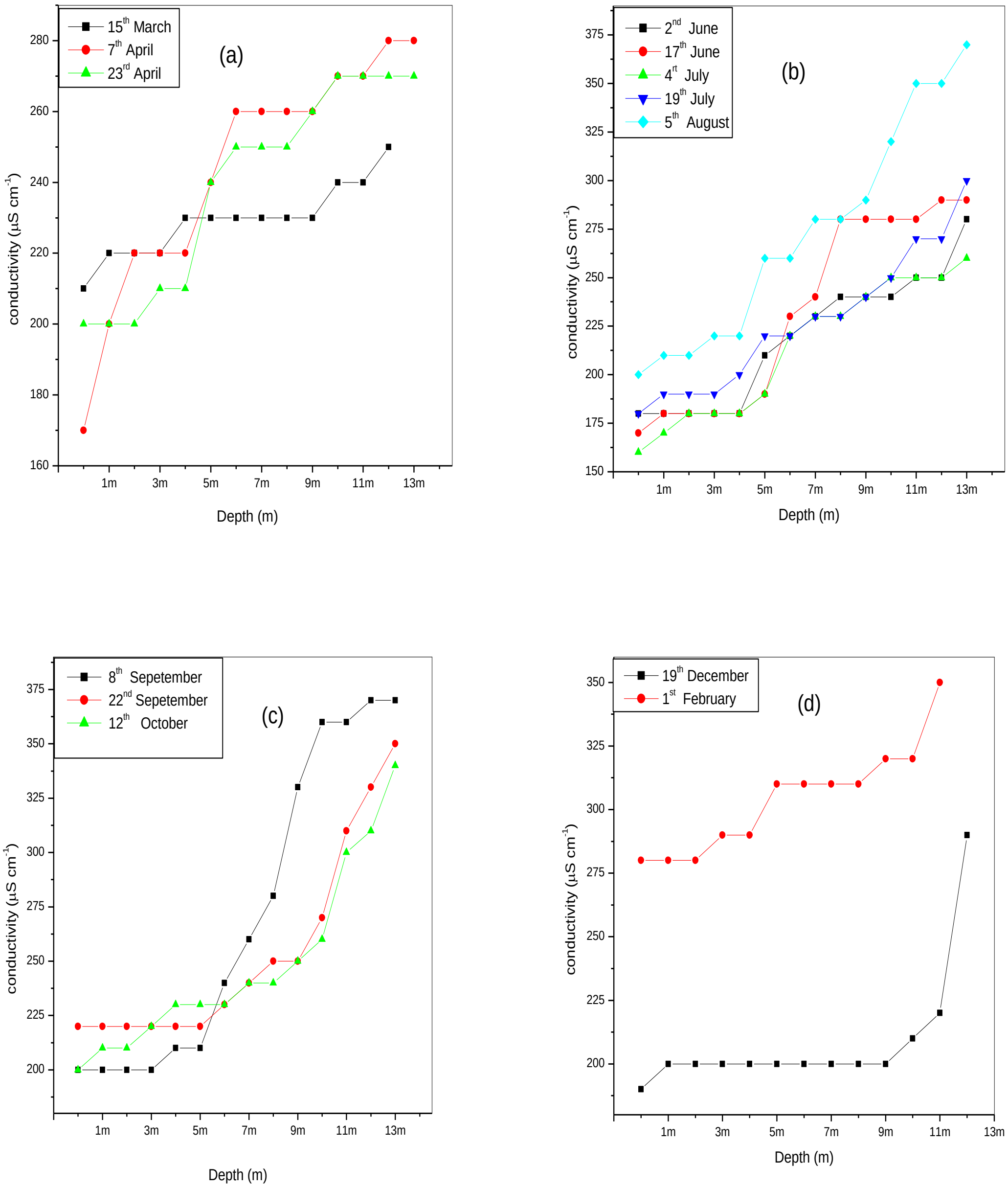

Figure 5.5: Variation in Conductivity (µS cm^{-1}) at different depths in Manasbal lake during stratification and circulation

Table 5.6: Variation in Dissolved Oxygen (mgl^{-1}) at different depths in Manasbal lake

Depth	**MONTH**												
	15th Mar	**7th Apr**	**23rd Apr**	**2nd Jun**	**17th Jun**	**4th Jul**	**19th Jul**	**5th Aug**	**8th Sept**	**22nd Sept**	**12th Oct**	**19th Dec**	**1st Feb**
0 m	7	8	8.4	8.4	8.4	6.4	6	6	6	6.4	5.5	4.2	9
1m	7	7.5	8	7.2	7.3	5.5	5	5.4	5.2	5.2	4.5	4	8.4
2m	6	6	7.2	7.2	6.4	4.8	4.6	4.4	4.8	4.2	4.3	3.6	7.5
3m	5.5	5.8	6.8	7.2	5.4	4.6	4.4	3.4	4.2	3.8	4	3.4	7.2
4m	5.3	5.8	6.4	6	4.2	4.4	4.3	3.2	2.8	3.8	3.9	3.4	6.6
5m	4.5	3.9	4	4	4.2	3.2	4.2	3.2	2.6	3.8	3.9	3.4	6.2
6m	4	3	3.6	3.6	3.8	3	3.5	2.8	1.2	3.8	3.8	2.6	6.2
7m	3	2.2	2.8	2.8	2.2	3	3.3	2	1.2	2.6	2.5	2.2	6
8m	2.5	2.2	2	1.6	2	2.2	2.6	1.8	anoxic	2	2	2	4.8
9m	2.3	2	1.6	0.8	1	1.8	1.9	1.8	anoxic	0.6	0.5	0.8	3
10m	1.5	1.3	1.2	0.4	1	1.2	1.1	1.4	anoxic	anoxic	anoxic	anoxic	2.8
11m	1	1.2	1.2	0.4	0.5	0.6	0.5	0.8	anoxic	anoxic	anoxic	anoxic	2
12m	anoxic	anoxic	anoxic	anoxic	anoxic	anoxic	anoxic	anoxic	anoxic	anoxic	anoxic	anoxic	
13m	anoxic	anoxic	anoxic	anoxic	anoxic	anoxic	anoxic	anoxic	anoxic	anoxic	anoxic	anoxic	

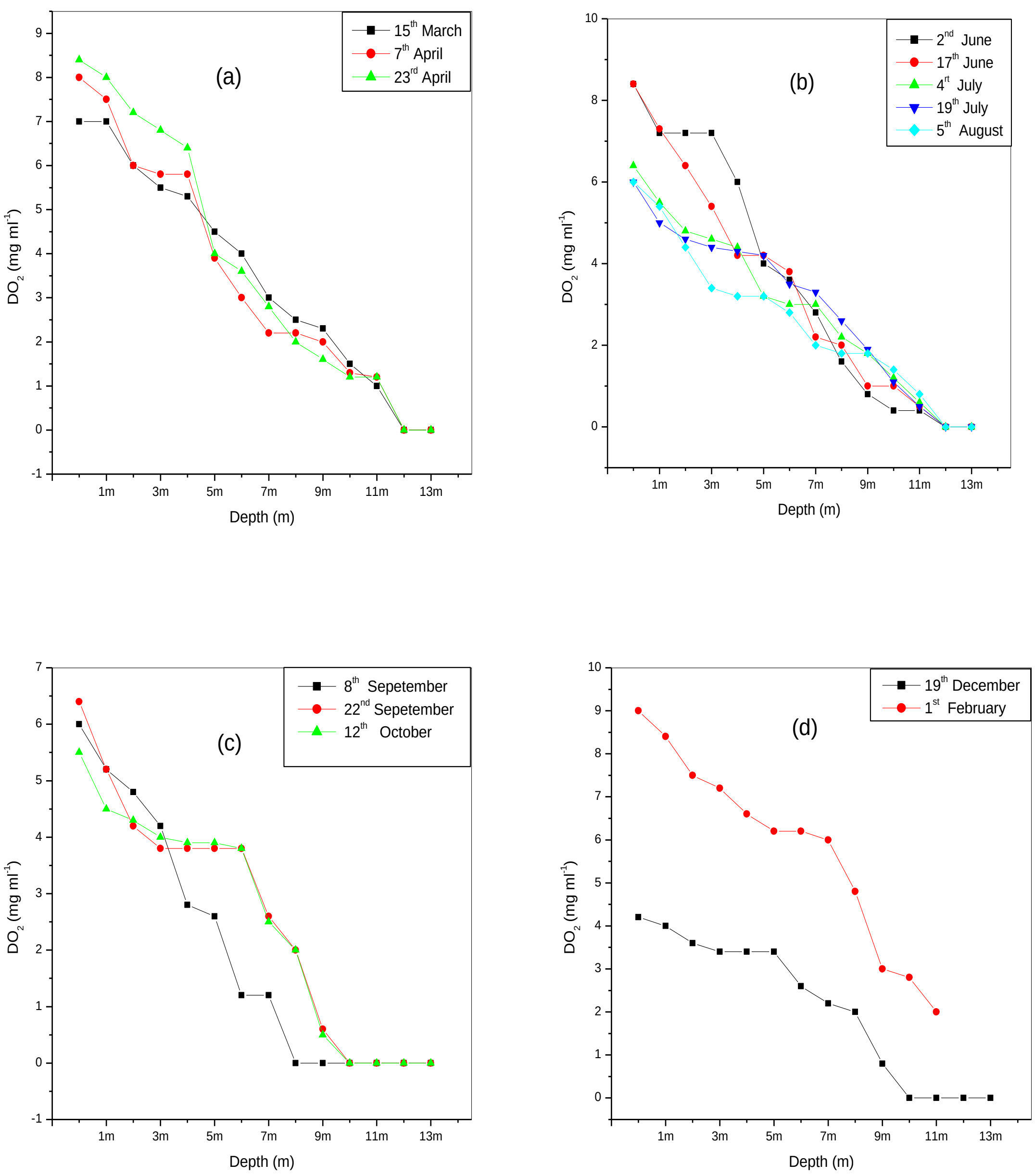

Figure 5.6 (I): Variation in Dissolved Oxygen (mgl^{-1}) at different depths in Manasbal lake during stratification and circulation

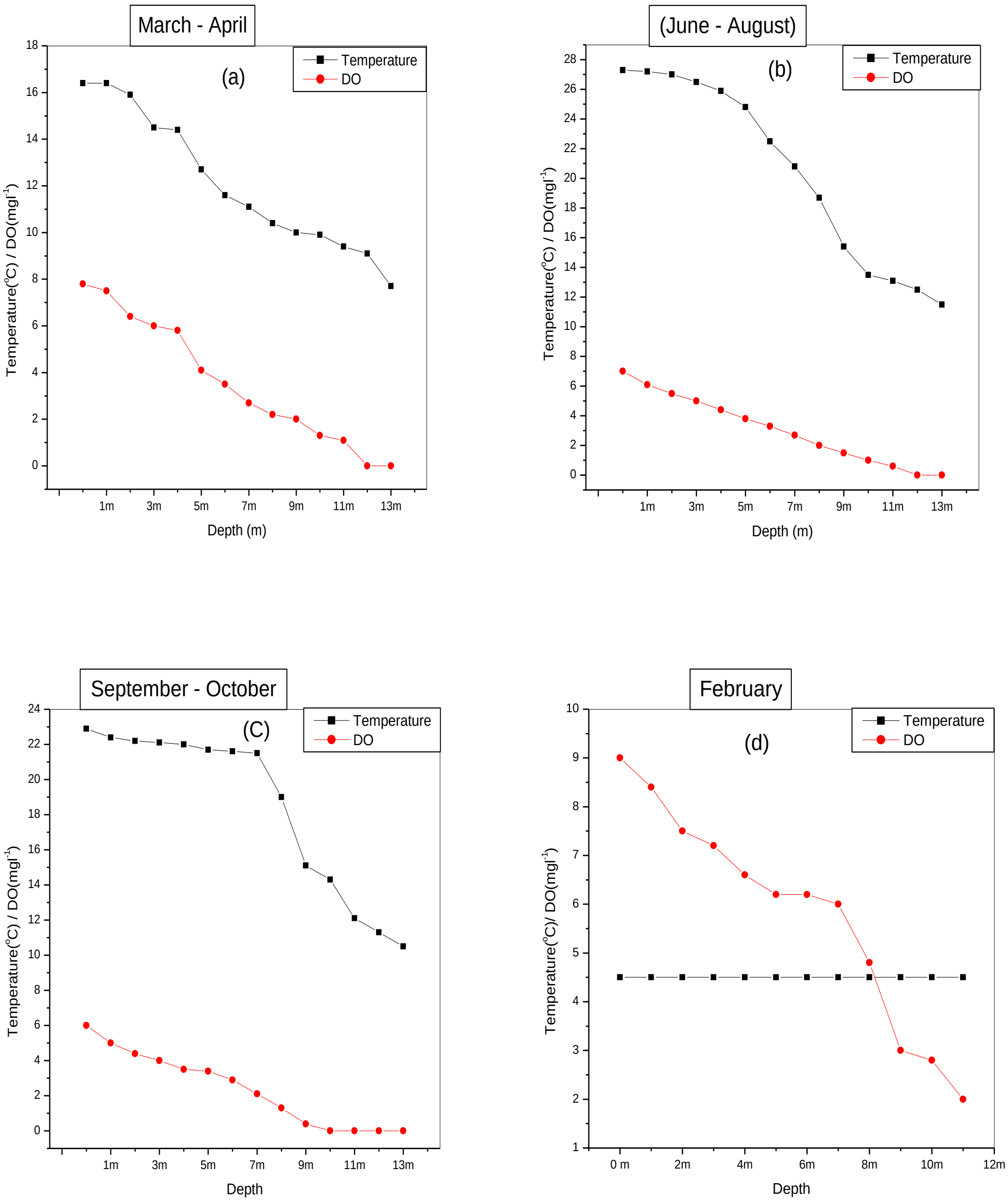

Figure 5.6 (II): Typical Dissolved Oxygen (DO) and Temperature (^{o}C) Patterns in Manasbal lakes

Table 5.7: Variation in Percent Oxygen Saturation (%) at different depths in Manasbal lake

Depth (m)	**MONTH**												
	15th Mar	**7th Apr**	**23rd Apr**	**2nd June**	**17th June**	**4th July**	**19th July**	**5th Aug**	**8th Sept**	**22nd Sept**	**12th Oct**	**19th Dec**	**1st Feb**
0m	86.41	93.04	111.7	123.95	128.65	98	94.28	94.28	91.89	92.19	69.32	44.57	84.41
1m	86.41	87.25	106.4	106.24	111.81	84.2	78.57	78.57	78.65	74.02	56.71	42.08	78.79
2m	72.6	69.14	93.67	106.24	98.02	72.6	71.35	72.28	71.7	59.78	54.19	37.87	70.3
3m	63.38	66.83	86.61	103.71	69.56	69.6	67.39	69.14	62.74	53.46	50.41	35.77	67.53
4m	61.07	66.2	81.51	86.42	62.74	65.7	64.23	52.74	41.82	53.46	48.64	35.77	61.9
5m	51.36	43.29	46.99	55.63	61.97	47.2	61.97	49.01	38.36	53.46	48.64	35.77	58.15
6m	44.81	32.7	40.33	46.83	54.73	41.7	48.68	47.8	17.7	53.46	47.4	27.35	58.15
7m	33.61	23.55	31.08	35.29	30.59	40.8	43.87	41.31	17.7	36.58	31.18	23.14	56.27
8m	28	23.35	24.2	20.16	25.74	28.3	33.46	28.13	0	27.81	23.96	21.04	45.02
9m	25.76	21.04	16.83	9.39	11.52	21.6	22.76	25.03	0	7.97	5.76	8.417	28.13
10m	16.8	13.67	12.62	4.69	11.52	14.1	12.92	16.94	0	0	0	0	26.26
11m	11.2	12.1	12.62	4.6	4.76	7.04	4.85	8.88	0	0	0	0	18.75
12m	0	0	0	0	0	0	0	0	0	0	0	0	
13m		0	0	0	0	0	0	0	0	0	0	0	

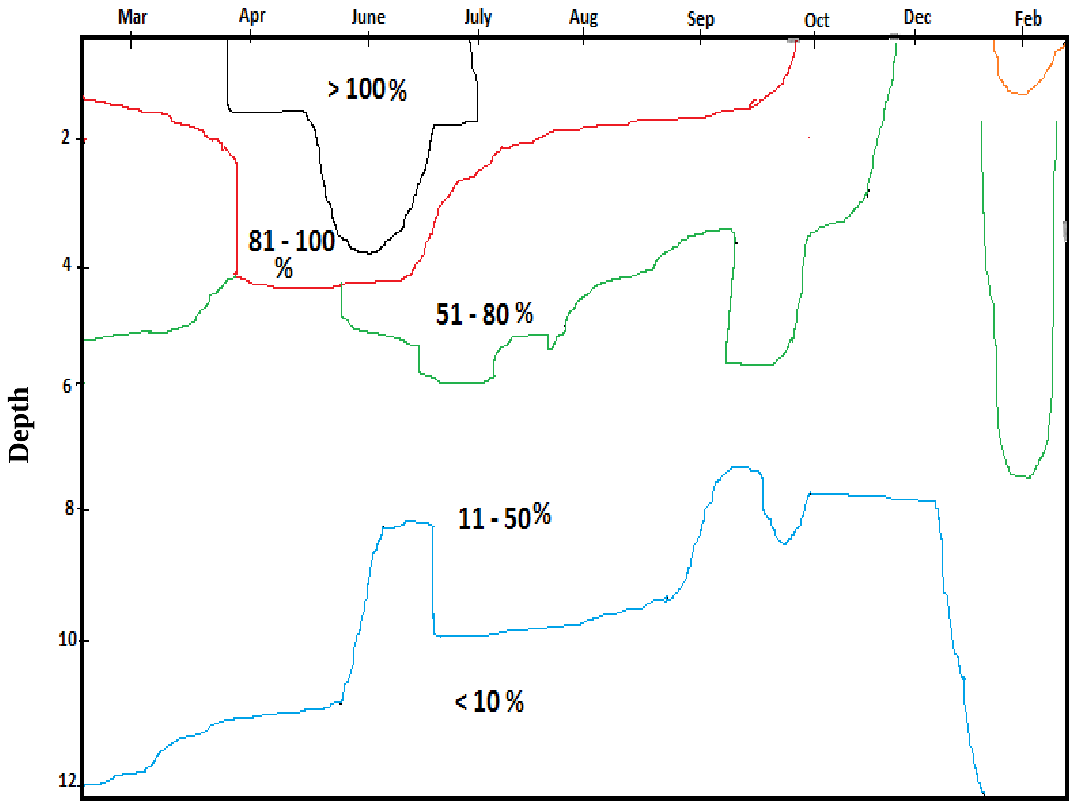

Figure 5.7 (I): Isopleths of Percent Oxygen Saturation (%) in Manasbal Lake

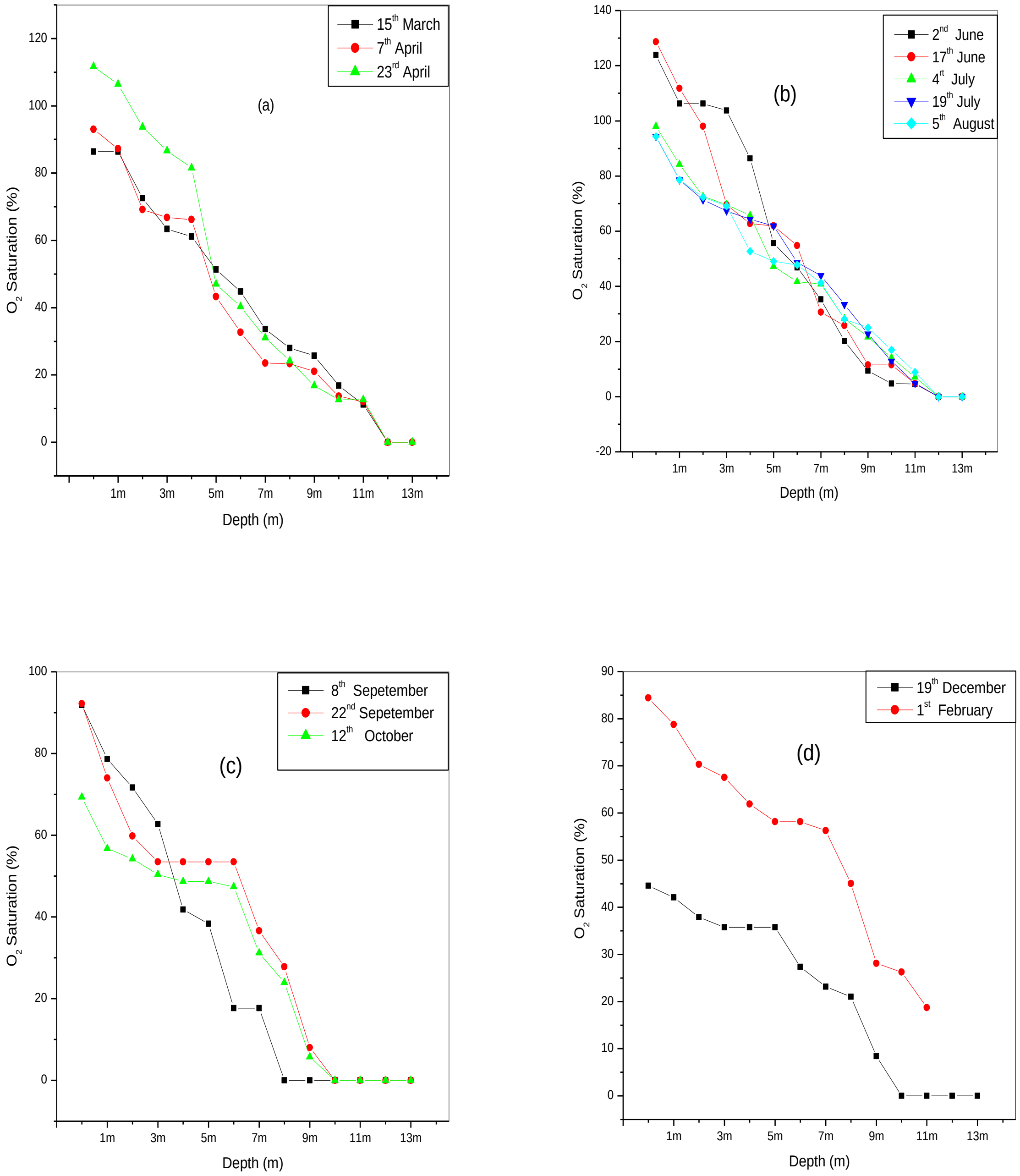

Figure 5.7 (II): Percent Oxygen Saturation in Manasbal lake at different depths sduring stratification and circulation

Table 5.8: Variation in Total Alkalinity (mgl^{-1}) at different depths in Manasbal lake

Depth (m)	MONTH												
	15th Mar	7th Apr	23rd Apr	2nd June	17th June	4th July	19th July	5th Aug	8th Sept	22nd Sept	12th Oct	19th Dec	1st Feb
0 m	152	155	151	131	125	123	124	124	136	151	155	163	174
1m	155	155	157	131	134	138	143	142	138	151	159	163	182
2m	157	157	159	144	145	145	144	144	140	156	163	175	184
3m	159	159	161	151	145	146	144	146	144	159	163	175	186
4m	175	168	163	153	148	147	151	146	146	162	166	187	186
5m	179	169	171	165	151	168	176	176	150	162	176	187	188
6m	179	171	187	166	151	175	183	186	153	164	176	189	188
7m	183	172	193	167	185	187	192	191	154	164	176	193	188
8m	185	173	193	172	188	190	193	192	154	165	182	195	190
9m	189	186	199	189	191	192	195	194	158	171	185	197	190
10m	189	190	203	189	194	196	202	197	158	173	188	197	190
11m	193	191	205	196	196	197	203	199	166	184	188	199	192
12m	197	190	215	197	201	199	204	202	173	185	197	199	
13m		202	221	199	205	205	206	205	178	188	197		

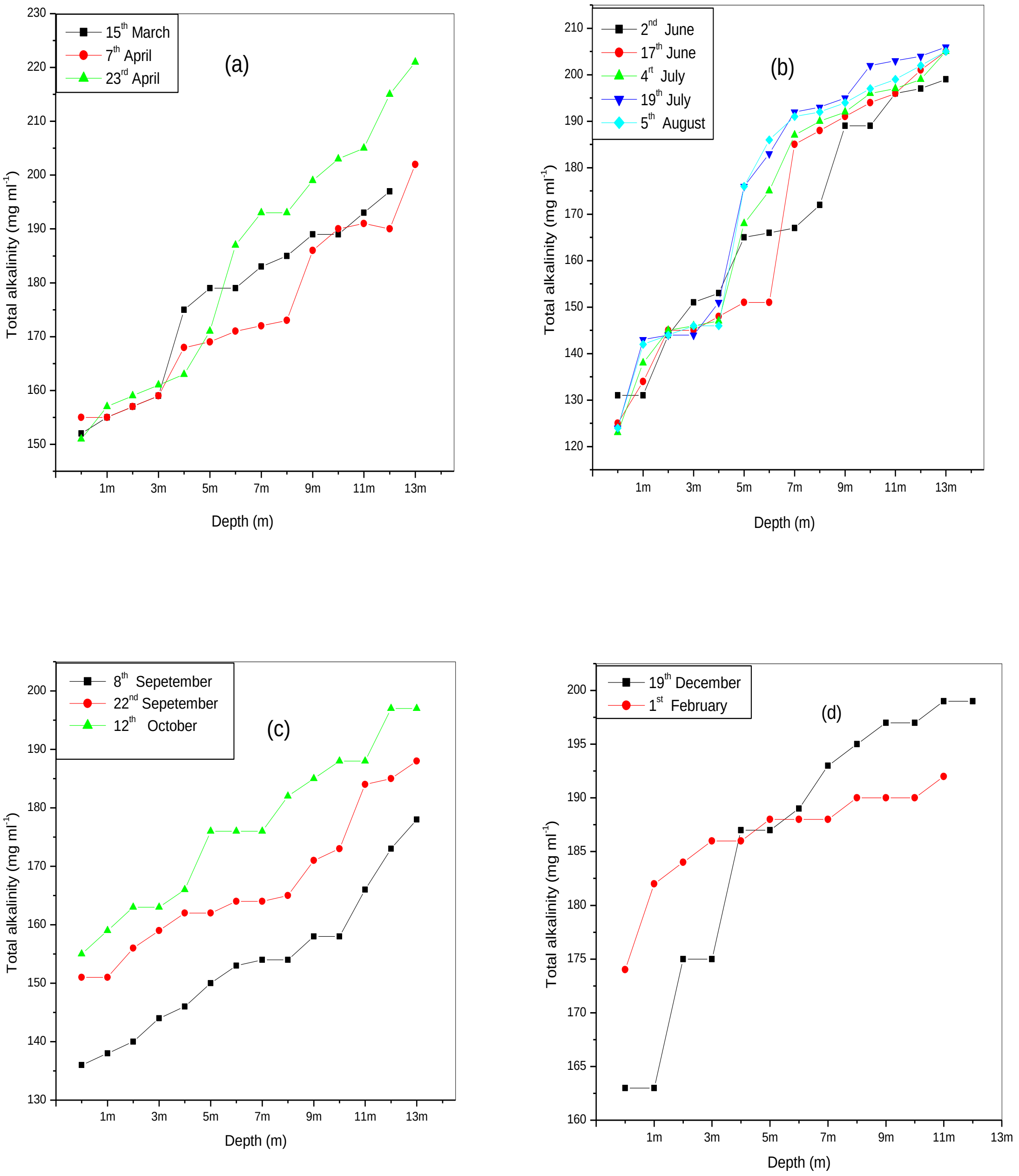

Figure 5.8: Variation in Total Alkalinity (mgl^{-1}) at different depths in Manasbal lake during stratification and circulation

Table 5.9: Variation in Free Carbon Dioxide (mgl^{-1}) at different depths in Manasbal lake

Depth (m)	MONTH												
	15th Mar	7th Apr	23rd Apr	2nd June	17th June	4th July	19th July	5th Aug	8th Sept	22nd Sept	12th Oct	19th Dec	1st Feb
0m	12	12.6	6	absent	absent	absent	absent	absent	absent	4	4	7	10
2m	12.6	14	8	absent	absent	absent	absent	absent	absent	4	5	7	10
4m	13.3	13.3	8	absent	absent	absent	absent	absent	absent	4	5	7	10
6m	13.3	16	8	10	absent	6	7	4	14	4	5	7	10
8m	15.3	20.7	8	18	6	8	9	10	14	10	12	7	10
10m	19	26	12	20	6	10	12	12	16	10	12	7	10
12m	22	32.6	12	20	8	14	16	12	16	18	16	20	
13m		40	20	20	8	16	16	24	18	18	18		

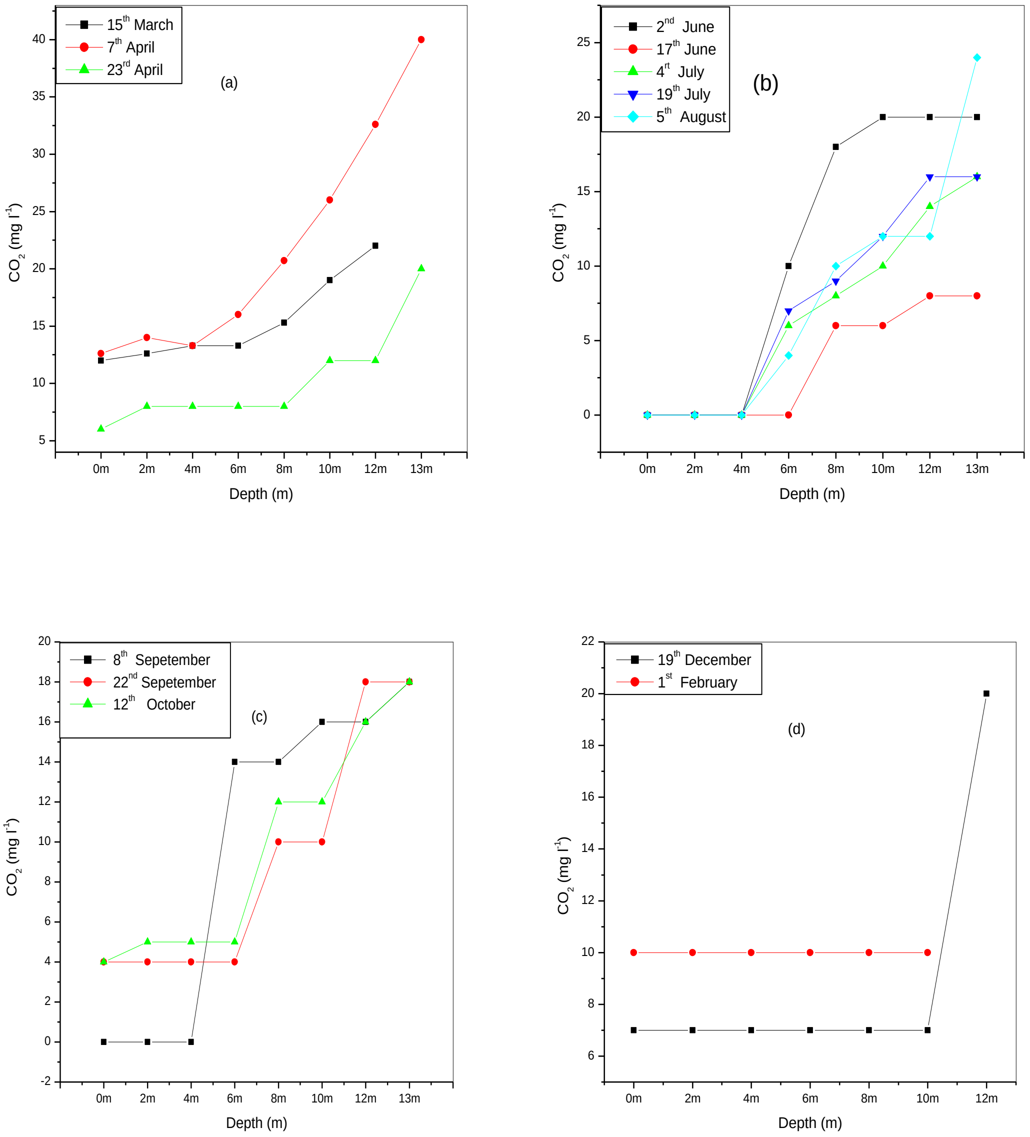

Figure 5.9: Variation in Free Carbon Dioxide (mgl^{-1}) at different depths in Manasbal lake during stratification and circulation

Table 5.10: Variation in Chloride (mgl^{-1}) at different depths in Manasbal lake

Depth (m)	MONTH												
	15th Mar	7th Apr	23rd Apr	2nd June	17th June	4th July	19th July	5th Aug	8th Sept	22nd Sept	12th Oct	19th Dec	1st Feb
0m	7.9	7.9	6.9	12.9	13.4	16.9	14.6	9.4	19.9	24.4	22.1	25.4	26.9
2m	9.9	10.9	6.9	14.9	13.4	16.9	14.9	12.3	20.4	26.4	23.4	27.4	26.9
4m	12.9	11s.9	6.9	14.9	14.9	18.9	15.6	12.9	22.9	28.9	26.4	27.4	27.9
6m	12.9	11.9	7.9	15.9	15.9	18.9	15.9	13.9	23.9	28.9	26.6	28.9	28.9
8m	14.9	12.9	8.9	15.9	16.9	19.9	16.9	14.4	24.4	28.9	27.6	28.9	31.9
10m	14.9	14.9	12.9	16.9	16.9	19.9	17.4	14.4	24.4	29.9	27.9	29.7	32.9
12m	16.7	16.9	13.9	16.9	17.9	19.9	18.9	16.9	25.9	30.9	27.9	30.8	
13m		16.9	13.9	19.9	19.9	23.9	20.1	16.9	26.9	32.9	27.9		

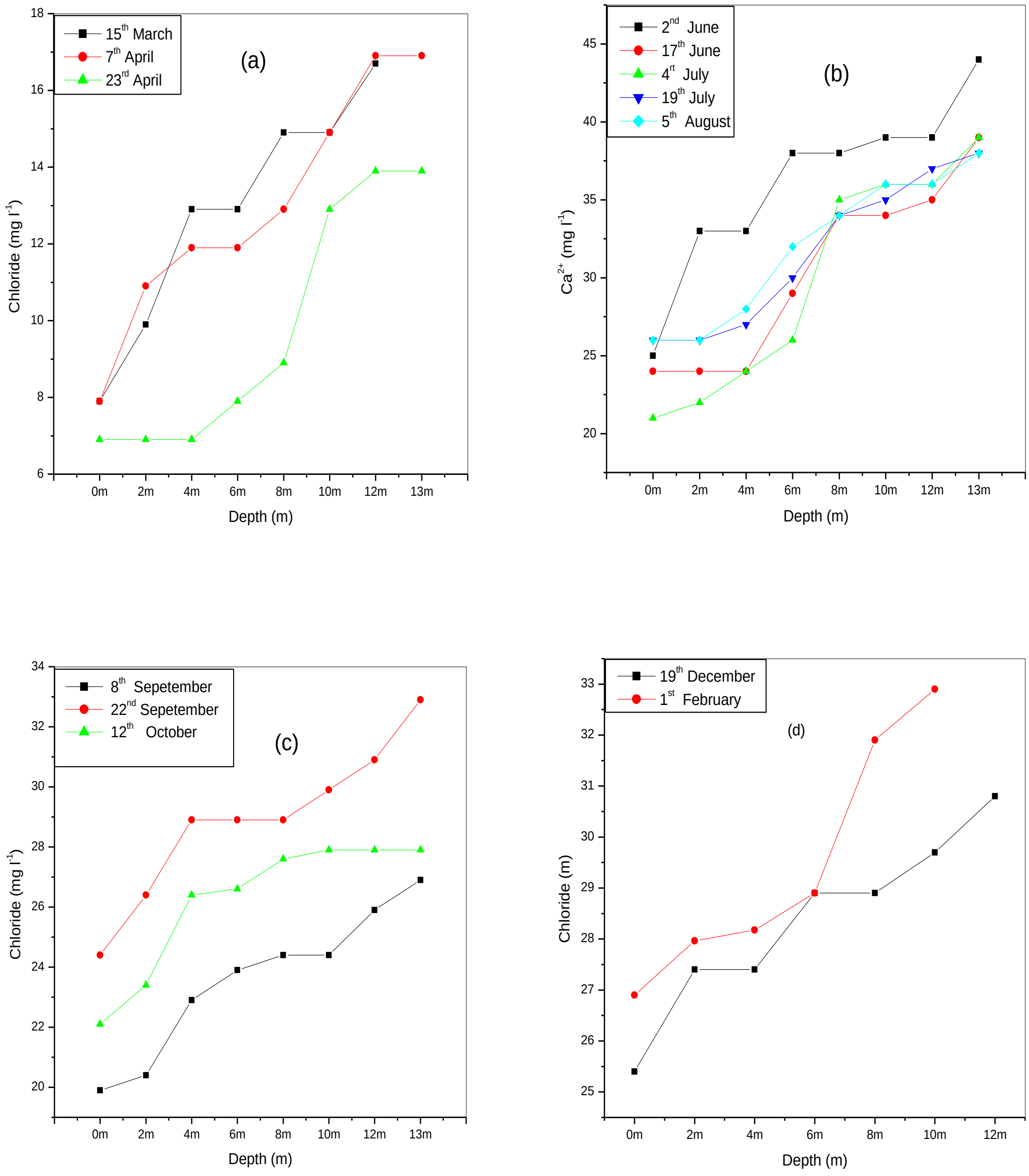

Figure 5.10: Variation in Chloride (mgl^{-1}) at different depths in Manasbal lake during stratification and circulation

Table 5.11: Variation in Total Hardness (mgl^{-1}) at different depths in Manasbal lake

Depth (m)	**MONTH**												
	15th Mar	**7th Apr**	**23rd Apr**	**2nd June**	**17th June**	**4th July**	**19th July**	**5th Aug**	**8th Sept**	**22nd Sept**	**12th Oct**	**19th Dec**	**1st Feb**
0m	124	112	122	86	80	64	83	86	98	97	99	98	120
2m	136	114	136	110	80	76	84	87	101	109	112	110	124
4m	136	132	140	110	80	80	85	92	116	117	120	131	135
6m	145	132	146	142	98	90	95	114	122	122	125	140	148
8m	162	134	150	150	112	118	124	129	146	148	154	148	154
10m	170	138	152	152	114	120	128	143	167	151	164	151	158
12m	196	164	154	152	117	120	135	144	187	153	170	153	
13m		176	168	164	130	128	138	159	206	163	178		

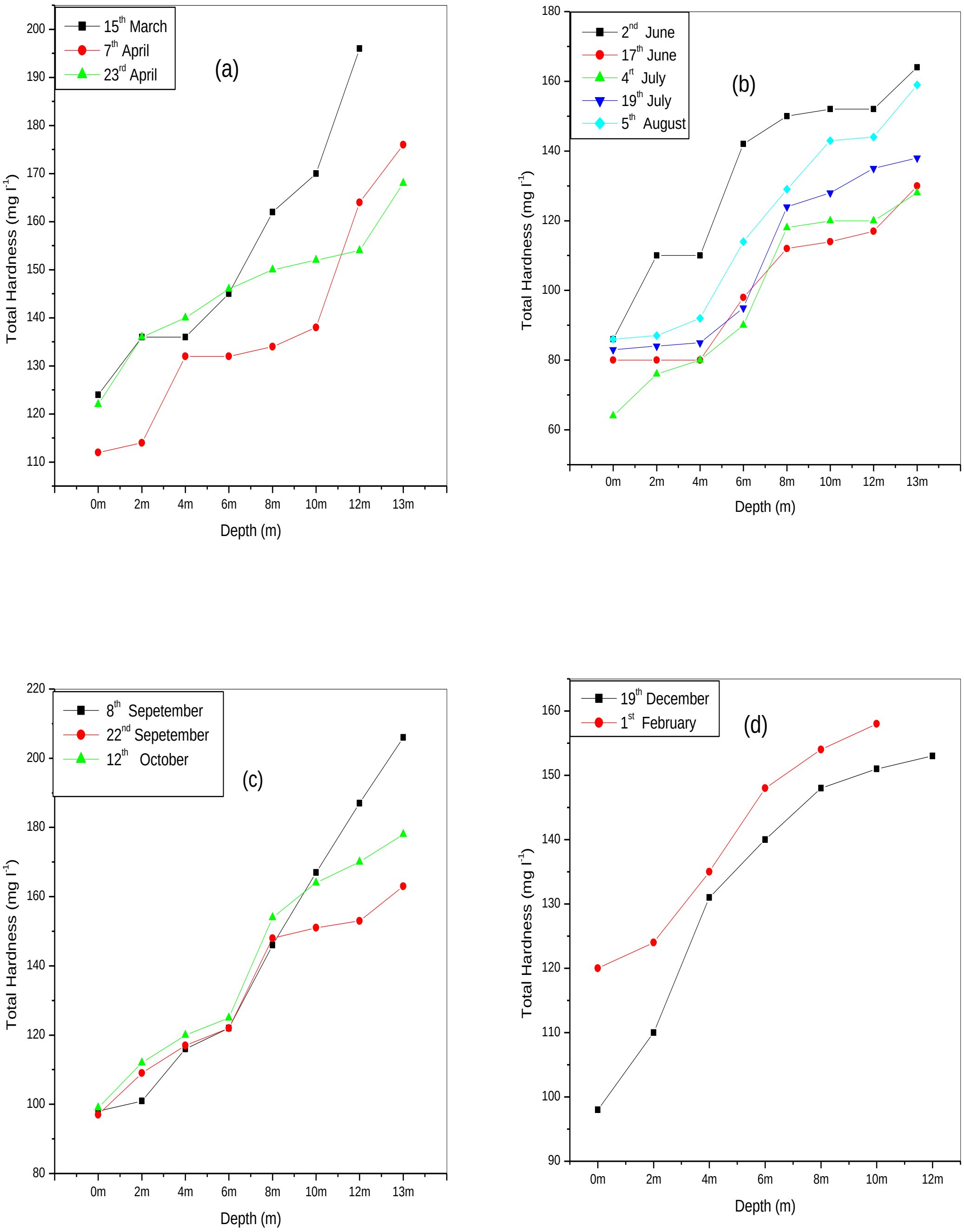

Figure 5.11: Variation in Total Hardness (mgl^{-1}) at different depths in Manasbal lake during stratification and circulation

Table 5.12: Variation in Calcium Hardness (mgl^{-1}) at different depths in Manasbal lake

Depth (m)	MONTH												
	15th Mar	7th Apr	23rd Apr	2nd Jun	17th Jun	4th Jul	19th Jul	5th Aug	8th Sept	22nd Sept	12th Oct	19th Dec	1st Feb
0m	86	86	88	64	60	54	65	65	67	73	71	76	84
2m	90	88	90	82	60	56	66	66	71	75	78	76	88
4m	90	98	94	82	60	60	67	70	81	82	85	95	94
6m	98	98	96	96	73	65	75	81	84	84	85	98	98
8m	104	100	100	96	85	88	85	85	93	95	97	98	98
10m	106	102	100	98	87	90	88	89	99	98	99	100	98
12m	109	128	100	98	87	90	94	90	115	100	103	102	
13m		138	112	110	98	98	96	95	125	102	108		

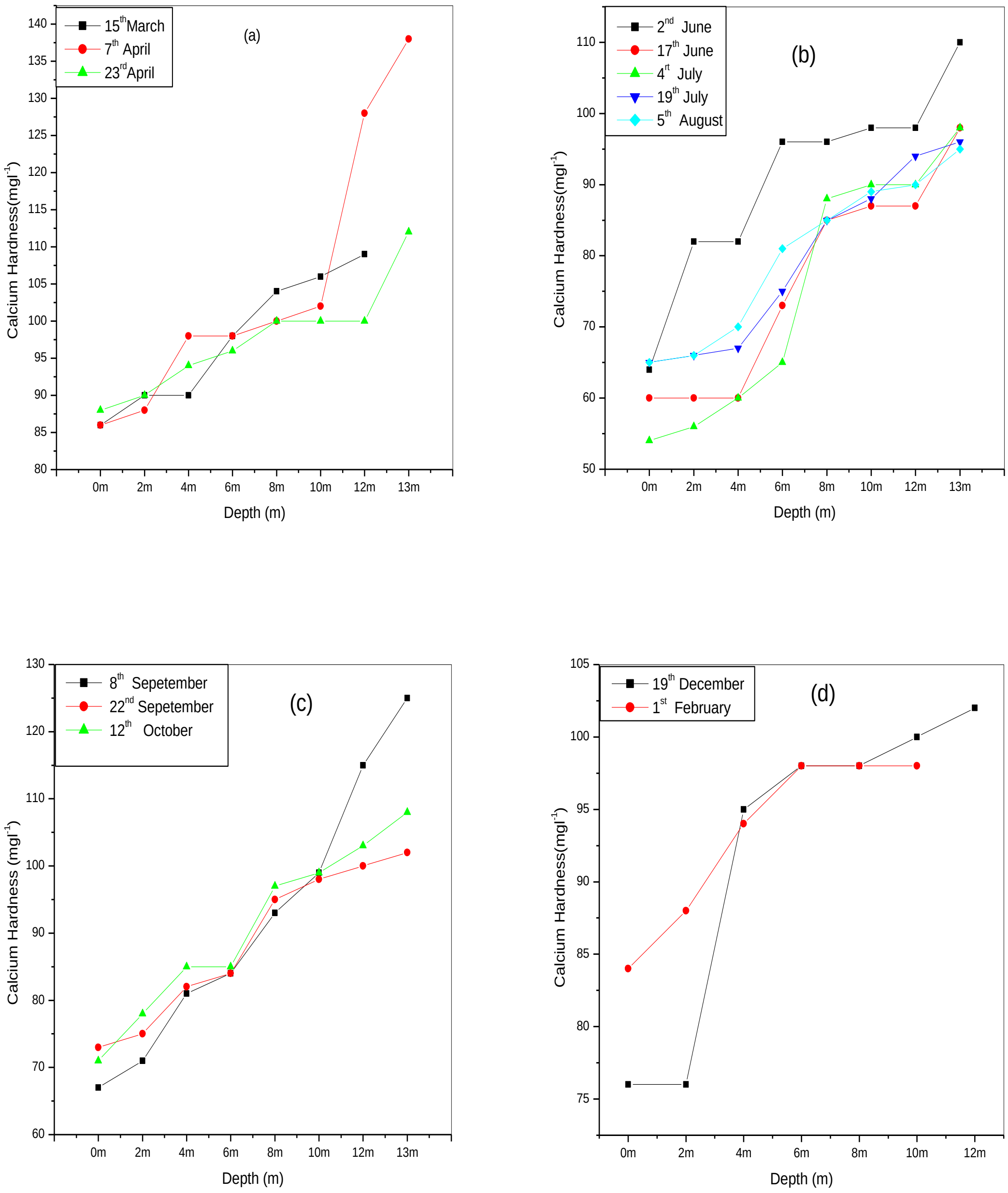

Figure 5.12: Variation in Calcium Hardness (mgl^{-1}) at different depths in Manasbal lake during stratification and circulation

Table 5.13: Variation in Calcium Content (mgl^{-1}) at different depths in Manasbal lake

Depth (m)	**MONTH**												
	15th Mar	**7th Apr**	**23rd Apr**	**2nd June**	**17th June**	**4th July**	**19th July**	**5th Aug**	**8th Sept**	**22nd Sept**	**12th Oct**	**19th Dec**	**1st Feb**
0m	34	34	35	25	24	21	26	26	26	29	28	30	33
2m	36	35	36	33	24	22	26	26	28	30	31	30	35
4m	36	39	37	33	24	24	27	28	32	33	34	38	38
6m	39	39	38	38	29	26	30	32	34	34	34	39	40
8m	41	40	40	38	34	35	34	34	37	38	38	39	40
10m	42	41	40	39	34	36	35	36	38	40	40	40	40
12m	43	51	40	39	35	36	37	36	46	40	42	42	
13m		55	45	44	39	39	38	38	50	41	43		

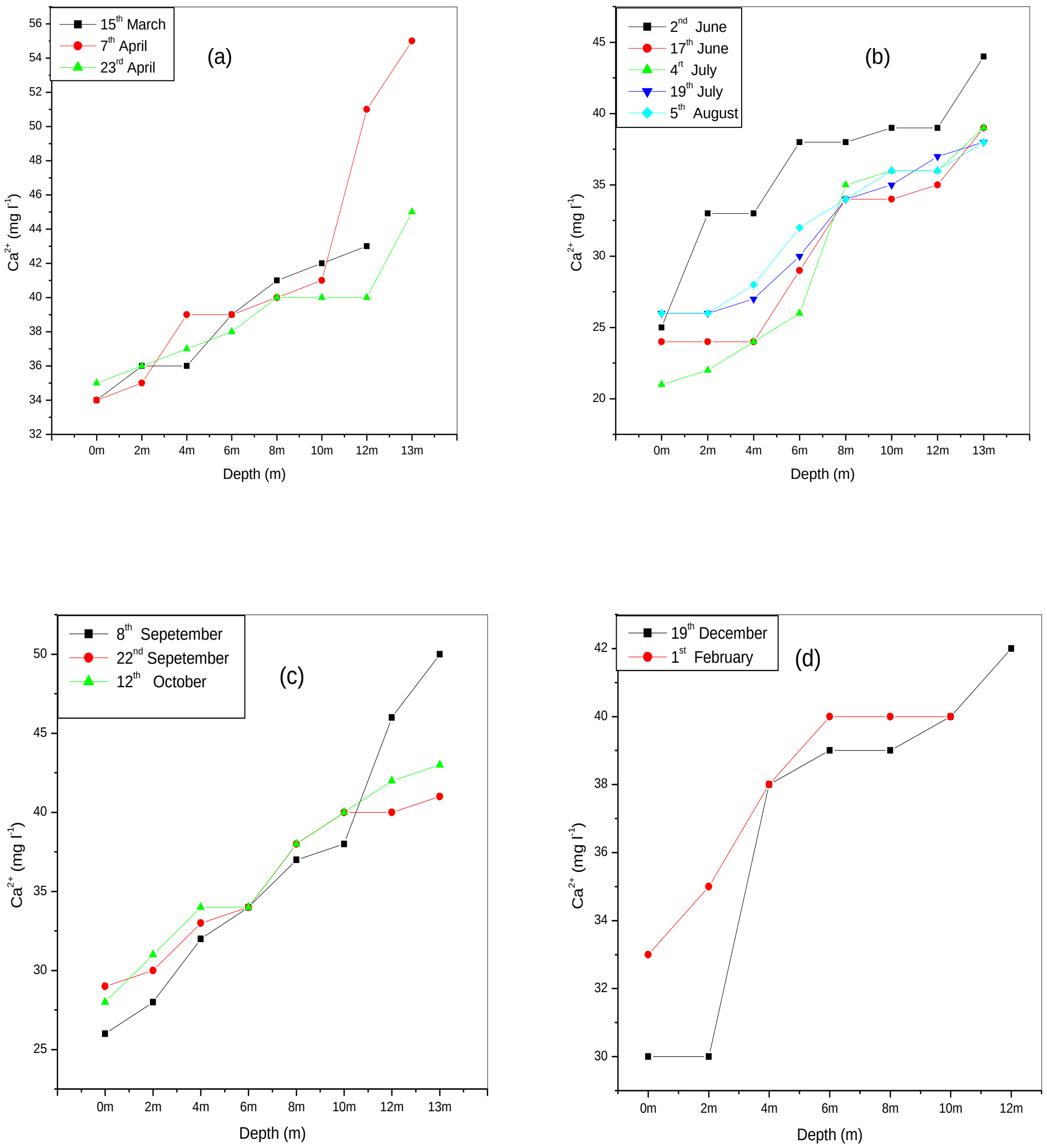

Figure 5.13: Variation in Calcium content (mgl^{-1}) at different depths in Manasbal lake during stratification and circulation

Table 5.14: Variation in Magnesium Hardness (mgl^{-1}) at different depths in Manasbal lake

Depth (m)	MONTH												
	15th Mar	7th Apr	23rd Apr	2nd June	17th June	4th July	19th July	5th Aug	8th Sept	22nd Sept	12th Oct	19th Dec	1st Feb
0m	38	26	34	22	20	10	18	21	21	24	28	22	36
2m	46	26	46	28	20	20	18	21	30	34	34	34	36
4m	46	34	46	28	20	20	18	22	35	35	35	36	41
6m	47	34	50	46	25	25	20	33	38	38	40	42	50
8m	58	34	50	54	27	30	39	44	53	53	57	50	56
10m	64	36	52	54	27	30	40	54	68	53	65	51	60
12m	87	36	54	54	30	30	41	54	72	53	67	51	
13m		38	56	54	32	30	42	64	81	61	70		

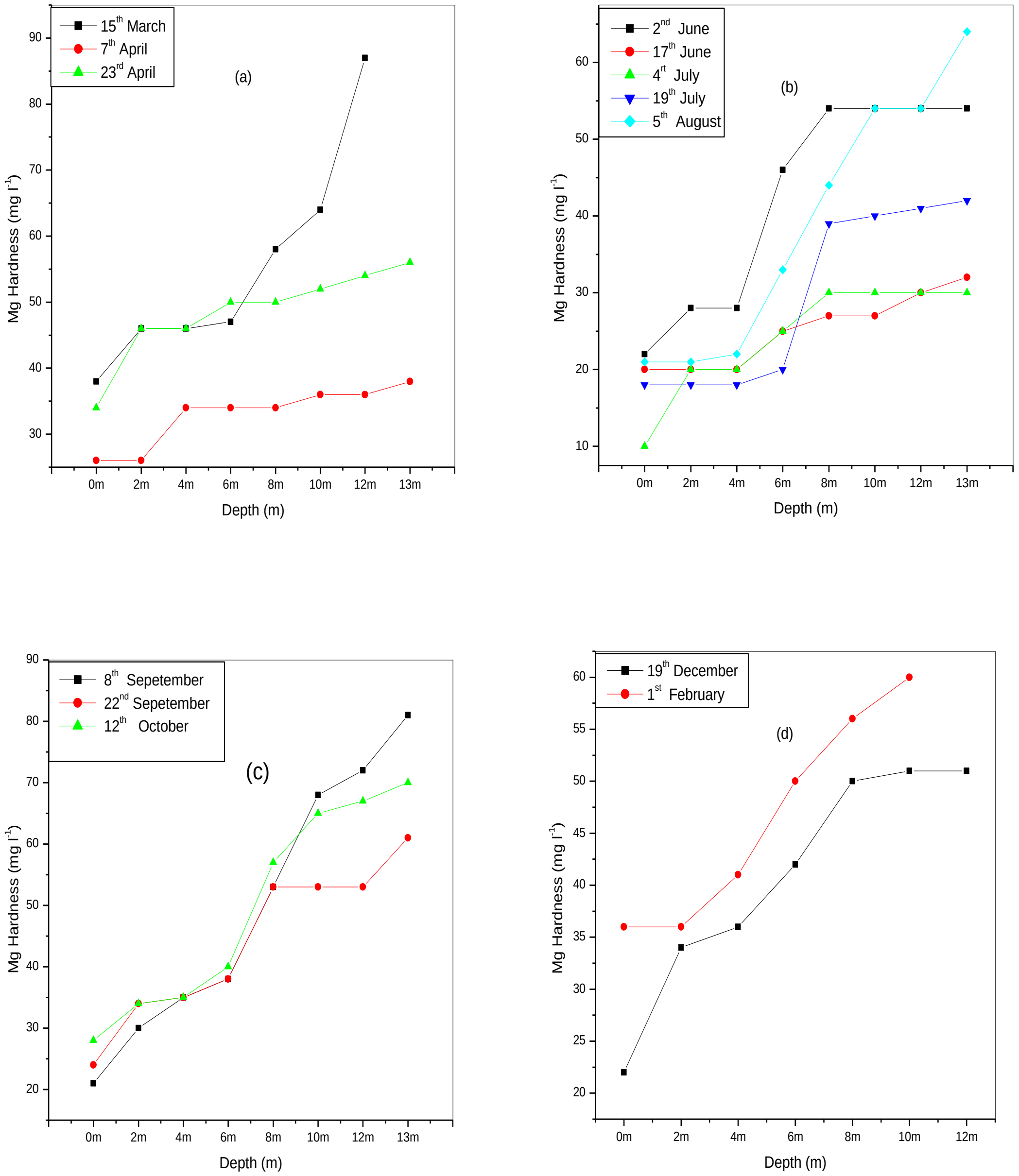

Figure 5.14: Variation in Magnesium Hardness (mgl^{-1}) at different depths in Manasbal lake during stratification and circulation

Table 5.15: Variation in Magnesium content (mgl^{-1}) at different depths in Manasbal lake

Depth (m)	MONTH												
	15th Mar	7th Apr	23rd Apr	2nd June	17th June	4th July	19th July	5th Aug	8th Sept	22nd Sept	12th Oct	19th Dec	1st Feb
0m	9	6	8	5	4	3	4	5	7	6	7	5	8
2m	11	6	11	6	4	4	4	5	7	8	8	8	8
4m	11	8	11	6	4	4	4	5	8	8	8	8	10
6m	11	8	12	11	6	6	4	8	9	9	9	10	12
8m	14	8	12	13	6	7	9	10	12	12	13	12	13
10m	15	8	12	13	6	7	9	13	16	12	15	12	14
12m	21	8	13	13	7	7	10	13	17	12	16	12	
13m		9	13	13	7	7	10	15	19	14	17		

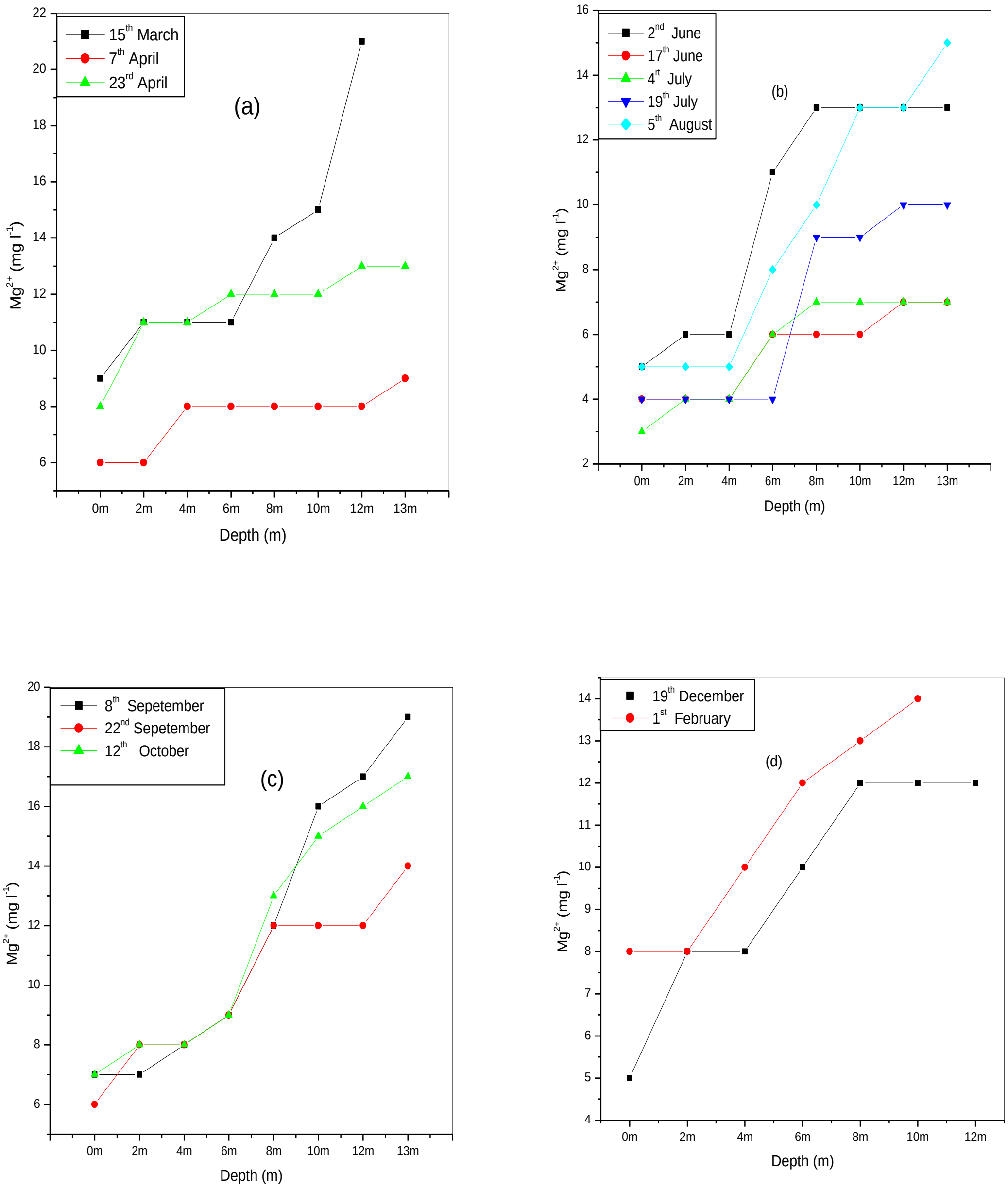

Figure 5.15: Variation in Magnesium content (mgl^{-1}) at different depths in Manasbal lake during stratification and circulation

Table 5.16: Variation in Orthophosphate ($\mu g l^{-1}$) at different depths in Manasbal lake

Depth (m)	MONTH												
	15th Mar	**7th Apr**	**23rd Apr**	**2nd June**	**17th June**	**4th July**	**19th July**	**5th Aug**	**8th Sept**	**22nd Sept**	**12th Oct**	**19th Dec**	**1st Feb**
0m	7	traces	7	6	6	traces	6	24	26	23.3	24	traces	6.8
2m	7	8	7	4	6	traces	6	26	26	26.3	25	26	15
4m	17	48.6	5	4	6.5	16.1	11	28	26	30.4	28	traces	17
6m	32	traces	6	6	6.5	traces	6	18	6	30.4	23	43.9	17
8m	39	traces	23	8	26	42	34	20	6	35.2	23	traces	18
10m	45	66	6	18.9	4	16.5	10.2	21	6	36.9	23	25	20
12m	48	66	27	63	30	30	30	41	23	60.6	48	132	
13m		68	45	63	133	133	102	55	42.5	68.9	59		

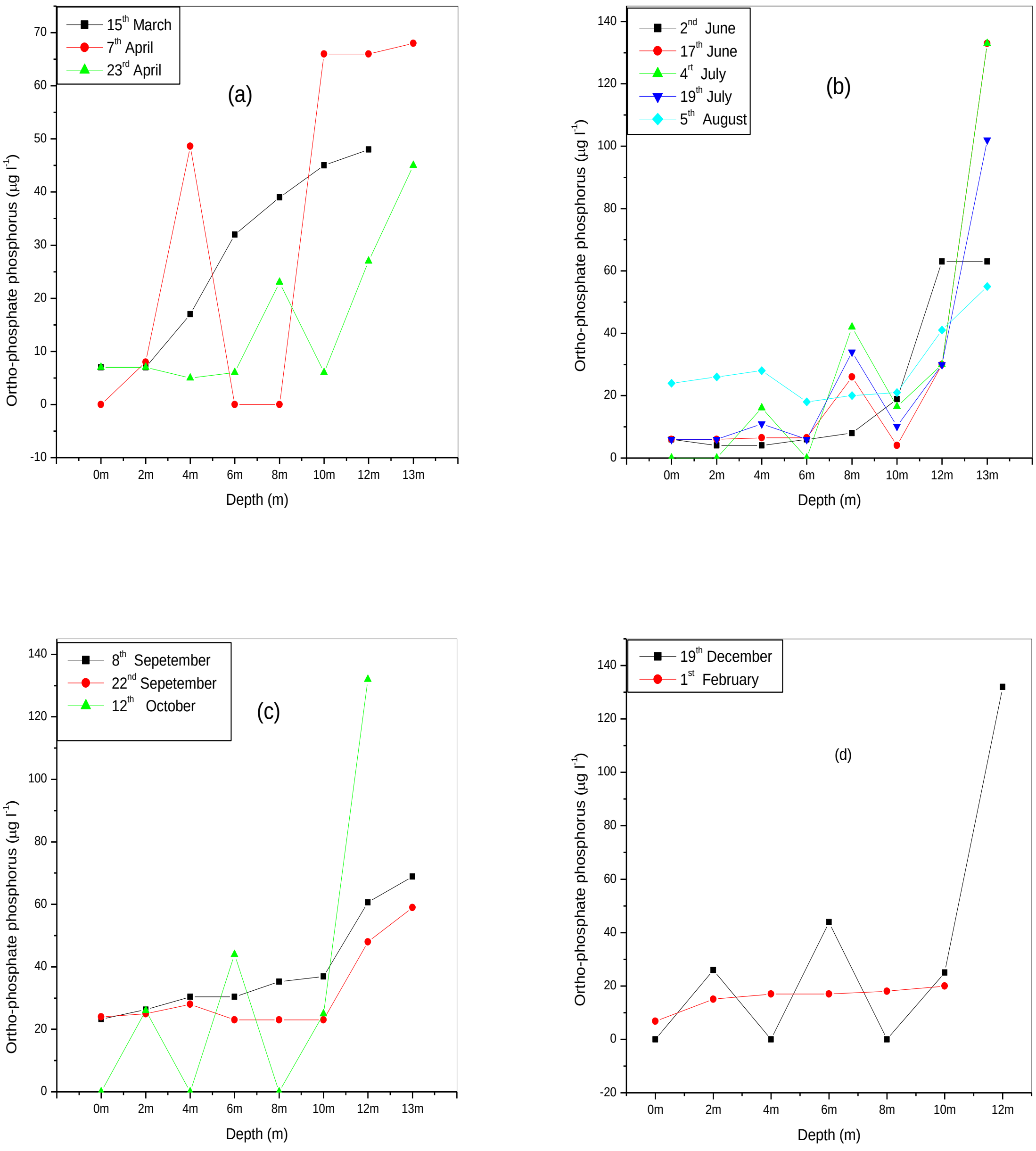

Figure 5.16: Variation in Orthophospate (µgl^{-1}) at different depths in Manasbal lake during stratification and circulation

Table 5.17: Variation in Total Phosphorus (μgl^{-1}) at different depths in Manasbal lake

Depth (m)	**MONTH**												
	15th Mar	**7th Apr**	**23rd Apr**	**2nd June**	**17th June**	**4th July**	**19th July**	**5th Aug**	**8th Sept**	**22nd Sept**	**12th Oct**	**19th Dec**	**1st Feb**
0m	170	42	299	139	152	274	232	190	146	102	105	124	64
2m	136	43	98.6	139	200	274	203	133	117	102	104	109	64
4m	45.3	277	180	143	200	200	182	164	133	103	104	118	64
6m	43	112	181	134	200	273	236	265	161	158	123	109	64
8m	136	400	178	139	274	202	238	334	200	167	125	133	64
10m	142	137	120	224	676	494	585	262	143	173	138	84	49
12m	220	148	227	233	576	409	492	406	154	188	154	38	

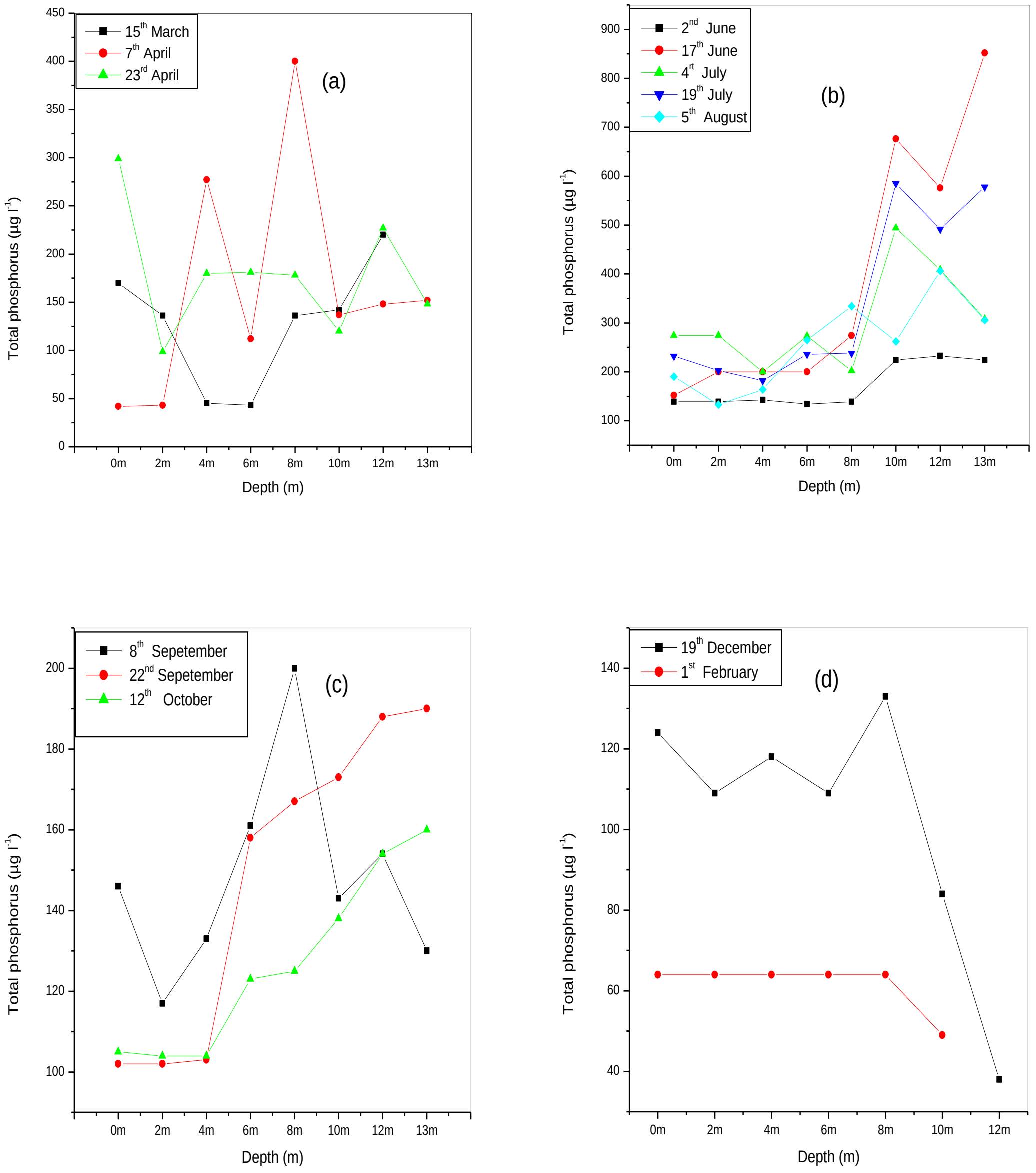

Figure 5.17: Variation in Total Phosphorus (µgl^{-1}) at different depths in Manasbal lake during stratification and circulation

Table 5.18: Variation in Ammonium-nitrogen (μgl^{-1}) at different depths in Manasbal lake.

Depth (m)	**MONTH**												
	15th Mar	**7th Apr**	**23rd Apr**	**2nd June**	**17th June**	**4th July**	**19th July**	**5th Aug**	**8th Sept**	**22nd Sept**	**12th Oct**	**19th Dec**	**1st Feb**
0m	68.8	22	74	20	34	75	59	44.8	44.8	74	59	122.8	30
2m	68.8	9	38.4	56	54.5	82	68	55.6	65.3	82	73	112	30
4m	68.8	22	69.7	56	88	76	66	57	65.3	97.9	81	102.4	35
6m	86	104.4	93.6	78.4	105.5	105	81	57	84.8	96.5	90	105.6	57
8m	91.9	205	261	646	538	269	183	97	172	83	127	82.8	57
10m	99	105	261	718	403	806	489	173.6	648.6	376	254	136.9	80
12m	99	97.9	330	839	722	969	579	190	744	415	356	354.7	
13m		99	427	986	844	975	673	243	754	501	407		

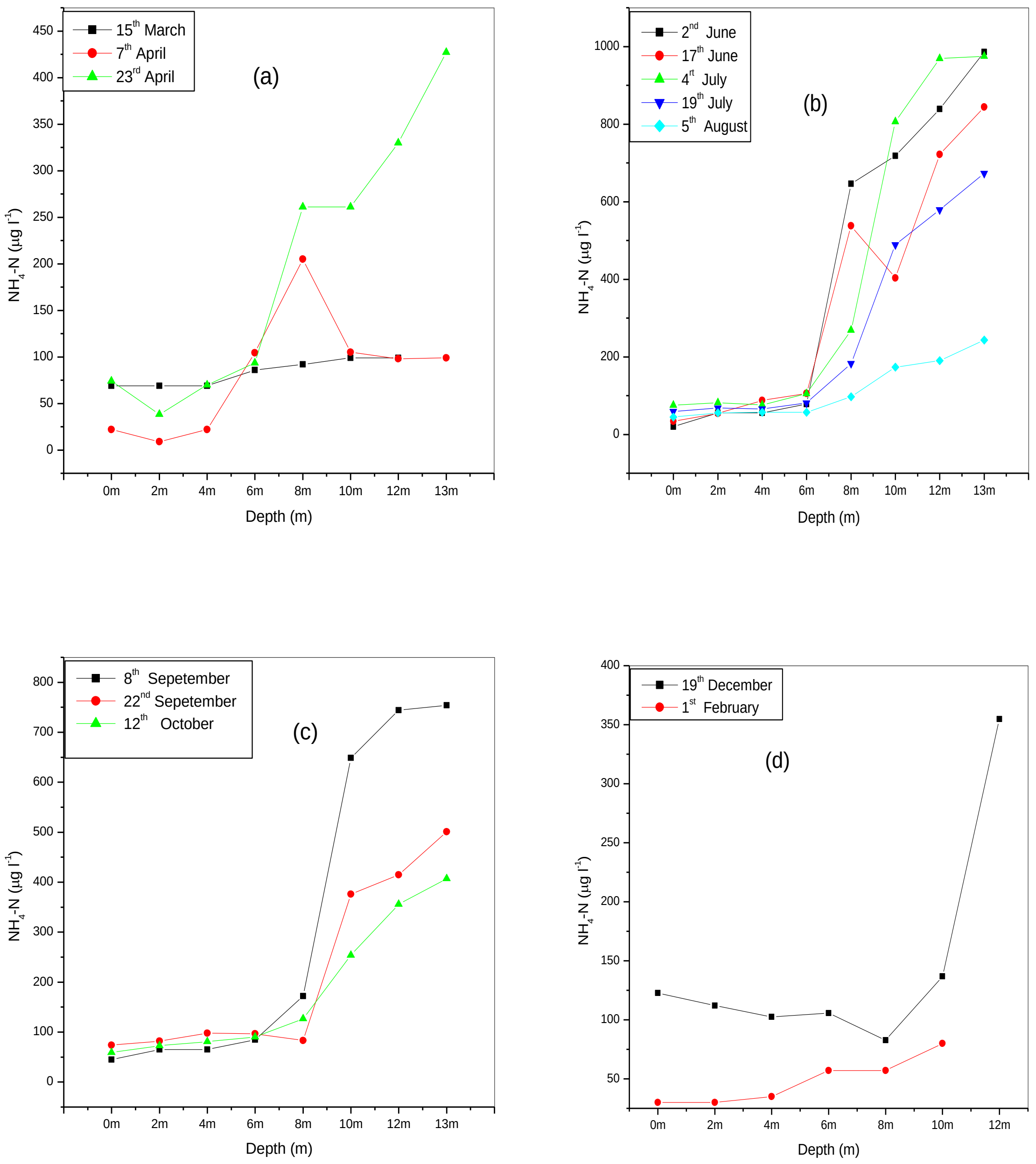

Figure 5.18: Variation in Ammonium - N (µgl^{-1}) at different depths in Manasbal lake during stratification and circulation

Table 5.19: Variation in Nitrate-nitrogen (μgl^{-1}) at different depths in Manasbal lake

Depth (m)	MONTH												
	15th Mar	7th Apr	23rd Apr	2nd June	17th June	4th July	19th July	5th Aug	8th Sept	22nd Sept	12th Oct	19th Dec	1st Feb
0m	97	22.6	39.3	67.2	20	137	78	traces	9.6	31.7	20.3	25.8	52.4
2m	128	22.6	43.8	55.5	12.4	82.8	47	5.7	24	25	23	16.8	54.5
4m	211	33.4	47.9	21.9	traces	13.3	12.6	55	38.8	41	39	29.5	55
6m	356	395	48	176.2	7.6	74.4	41	48	24.5	28	26	21.3	78
8m	228	222	63.4	67.5	137	40	88	102.6	301	180	290	29.5	78
10m	224	225	260	65	39.3	53.6	46	832	840	70	151	30	95
12m	228	227	290	44	21.3	41.2	31	50.3	988	270	229	45.6	
13m		243	270	178.5	111.3	64.5	87	304	800	330	349		

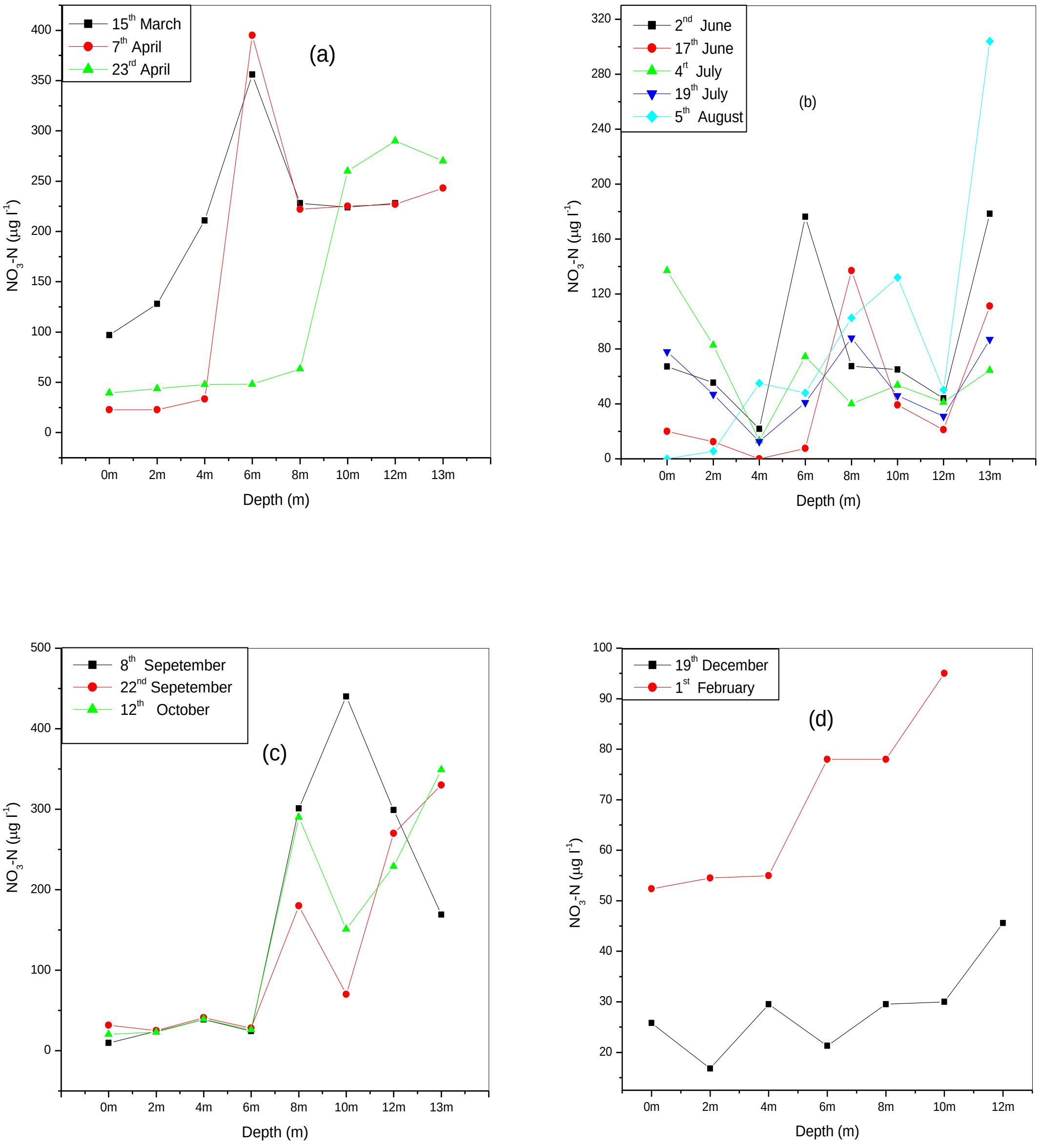

Figure 5.19: Variation in Nitrate – N (µgl^{-1}) at different depths in Manasbal lake during stratification and circulation

Table 5.20: Variation in Nitrite-nitrogen (μgl^{-1}) at different depths in Manasbal lake

Depth (m)	**MONTH**												
	15th Mar	**7th Apr**	**23rd Apr**	**2nd June**	**17th June**	**4th July**	**19th July**	**5th Aug**	**8th Sept**	**22nd Sept**	**12th Oct**	**19th Dec**	**1st Feb**
0m	2	2.8	2.8	3.8	4.9	13	11	traces	3.1	2.7	2.9	16.6	7.4
2m	2	2.8	2.8	2.2	2	19.7	17	traces	5	2.7	3.8	23.3	3.2
4m	10.8	14.4	7.2	4.6	2	25.8	15.4	5	7.7	2.7	5.2	8.3	3.7
6m	13.4	14.4	traces	5	9.6	24.8	16.4	2	9.6	2.7	6.1	16.6	6.4
8m	7.2	5	9.5	8.6	7.8	19.7	14.3	9	9.6	2	6	13.8	3.7
10m	7.4	11.4	3.5	8.5	4.9	26.7	35.7	44.7	15.7	39.7	20.7	13.8	9.5
12m	20.6	9.5	65.7	12	13	37.3	40	37.3	30.3	12.4	21.3	8	
13m		11.9	66	14.8	5	44.7	41	37.3	65.7	32.4	39		

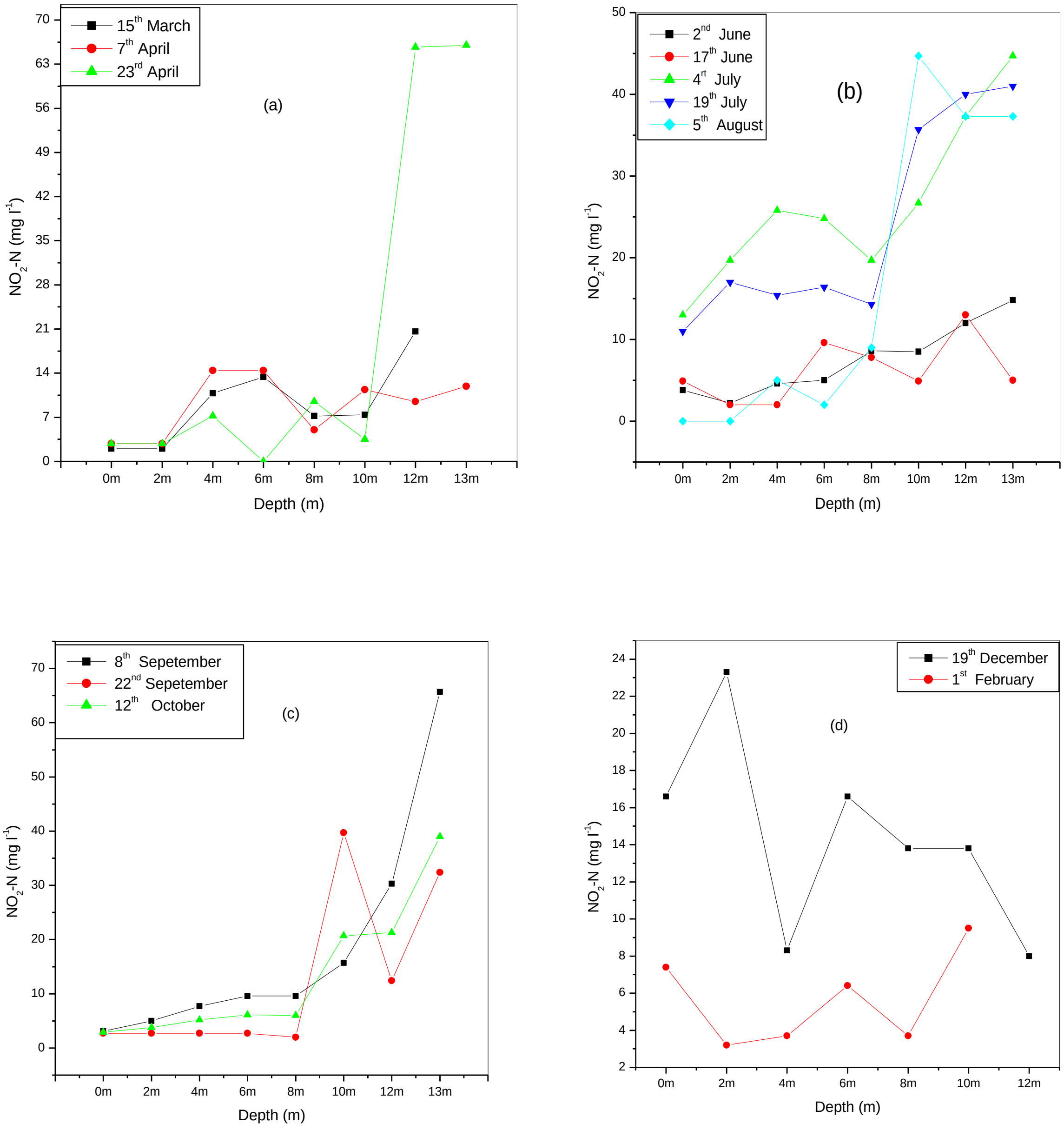

Figure 5.20: Variation in Nitrite – N (μgl^{-1}) at different depths in Manasbal lake during stratification and circulation

Table 5.21: Variation in TDS (mgl^{-1}) at different depths in Manasbal lake

Depth (m)	MONTH												
	15th Mar	**7th Apr**	**23rd Apr**	**2nd June**	**17th June**	**4th July**	**19th July**	**5th Aug**	**8th Sept**	**22nd Sept**	**12th Oct**	**19th Dec**	**1st Feb**
0 m	120	100	120	110	100	96	100	120	120	130	110	110	160
1m	130	120	120	100	110	100	110	120	120	130	110	120	160
2m	130	130	120	100	110	110	110	120	120	130	110	120	160
3m	130	130	130	100	110	110	110	130	120	130	130	120	170
4m	140	130	130	100	110	110	120	130	120	130	130	120	170
5m	140	140	140	120	110	110	130	150	120	130	130	120	180
6m	140	150	150	130	140	130	130	150	140	140	130	120	180
7m	140	150	150	140	140	130	140	170	150	140	140	120	180
8m	140	150	150	150	170	130	140	170	170	150	140	120	180
9m	140	150	160	150	170	140	140	170	200	150	150	120	180
10m	150	160	160	150	170	150	150	190	210	160	150	120	180
11m	150	160	160	160	170	150	160	210	210	190	180	130	210
12m	160	170	160	160	180	150	160	210	220	200	190	170	
13m		170	160	170	180	160	180	220	220	210	200		

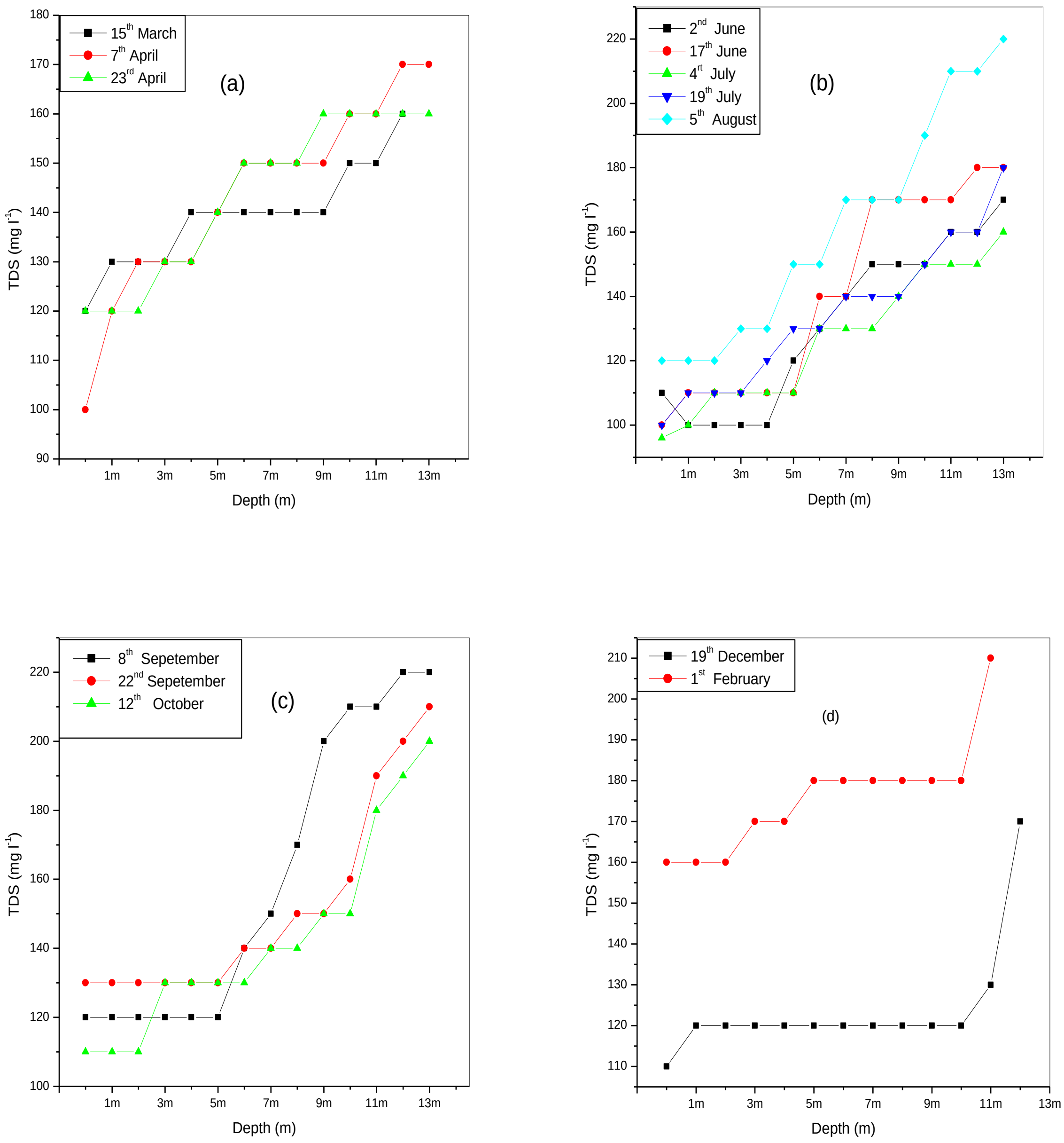

Figure 5.21: Variation in Total Dissolved Solids (mgl^{-1}) at different depths in Manasbal lake during stratification and circulation

CHAPTER – 6

DISCUSSION

The Manasbal is a warm monomictic lake with summer stratification starting in late February and lasting till November. Isothermic period covers two months December and January. Vass (1973) reported that the lake remained stratified from March to November. The investigation of Yousuf and Qadri (1978), Yousuf (1979) and Wangeneo (1984) has revealed that the isothermal period is limited to two months January – February. No inverse stratification has been reported in the lake. A perusal of literature on lakes reveals that the stratification influences the physico- limnology as well as depth distribution of different cations and anions in a lake.

The present data showed that the fluctuations in the water temperature follow more or less very closely those of the atmospheric temperature. Such a pattern of fluctuations has also been recorded by Yousuf (1979). Air temperature strongly influences lake temperature because it affects three important heat-exchange processes between water and the atmosphere - convective heat exchange, evaporative heat exchange, and the atmospheric emission of long-wave radi-ation (Edinger *et al*., 1968). Only on 17th June and 19th December, the temperature of surface water was recorded to be more than that of the atmosphere, which is attributable to the great heat retention capacity of the water and its slow cooling as compared to the quick changes in atmospheric temperature (Yousuf, 1979). The fluctuation in the ambient air as well as water temperature was found to influence nearly all the physico- chemical parameters, an observation in conformity with Wetzel (1983) and Kaya *et al*. (2010).

Seasonal changes in the solar radiation vis- a- vis atmospheric temperature produce characteristic pattern of circulation and stratification in deep waters (Vega *et al*., 1992). The data collected at the deepest point of the Manasbal lake depicted thermal stratification from March onwards, the lake remained stratified owing to the buoyant resistance of the surface waters till November, whereafter the winter overturn was observed during December -February. The winter overturn has also been reported by Yousuf and Qadri (1981) for this lake.

The study revealed that the width of thermocline varied continuously during study period. A similar phenomenon was observed by Yousuf (1979). With the onset of stratification of lake, the thermocline was established between 2m and 3m on 15th March and between 4m and 6m on 7th April. With the increase in temperature, the thermocline established between 2m and 6m on 23rd April, between 5m and 9m on 2nd June and 17th June. In July and 5th August, the thermocline was observed to be established between 5m and 10m and between 7m and 9m on 8th September and between 10m and 11m on 22nd September. Therefore with the passage of time, the lower boundary of thermocline gradually descended downward to 10m on 4th July and remained at this depth till circulation. The phenomenon, known as thermocline opening, was observed in the Lake Manasbal. A similar phenomenon of internal wave activity has been reported in Lake Kinneret (Antenucci *et al*., 2000). On 12th October, the thermocline was established between 8m and 9m. The maximum thickness of thermocline 5- 6m was found from 23rd April to 5th August, as shown in Fig. 5.2 (a & b).

The maximum depth (about 8m) of epilimnion was observed on 22nd September and 12th October, as shown in Fig. 5.3a. Although the thermal stratification continued through the month of October, the thermocline got restricted to just one meter, i.e. between 10m and 11m. On 19th December cooling of surface water had already set in, with the result that the whole water column shows a difference of just 0.4°C from surface to bottom. As a consequence the lake approached the isothermal conditions observed on 19th December and as well as on 1st February (Reid, 1961, Yousuf, 1979).

Present data indicated that the transparency undergoes a gradual decrease with the advancement of the summer stratification and the least values were recorded at the start and end of stagnation of the lake (Fig. 5.3b). Yousuf (1979) and Mackay *et al*. (2009) have also reported the influence of thermal stratification on transparency. It might be attributed to the fact that stratification increased the vertical density gradient and reduced the regeneration of nutrients from deep water sufficiently leading to reduced primary production, plankton density and ultimately increased water clarity (Verburg *et al*., 2003). Yousuf (1985) had also reported the rapid change in viscosity and the density of water in the thermocline zone which helps in the temporary checking of the settling materials, including bacteria, and thus offering better feeding opportunities to the zooplankton in this zone. This could be related to the higher transparency during the early stratification of the lake. From 5th August onwards transparency values in the lake started to decrease, which seems to be related to the downward extension of epilimnion (Fig. 5.3b) and mixing of water of epilimnion and upper thermocline region, resulting in the lowered transparency values. Studies of the relationship between water clarity, lake size and epilimnion depth in Canadian Shield lakes found that epilimnion depth is related to water clarity (Mazumder and Taylor, 1994; Fee *et al*., 1996). Lower transparency value during circulation period could be related to the complete mixing of the whole water column, which also result in the increase in the nutrients in the surface waters (Salmaso *et al*., 2002).

pH is one of the very significant chemical characteristic of all waters, which explains certain significant biotic and abiotic ecological characteristics of aquatic systems in general. pH of a water body is a diurnally variable property according to temperature variation in the system (Ojha and Mandloi, 2004).The Manasbal lake water is well buffered (Wanganeo, 1984).

The alkaline nature of water in the epilimnion and upper layers of thermocline of water depicted the eutrophic and mesotrophic status of water (Whitemore, 1989). Kaul and Handoo (1980) found that increased surface pH in water bodies is due to increased metabolic activities of autotrophs, because in general they utilize the CO_2 and liberate O_2 thus increasing H^+ ion concentration . The same authors are also of the opinion that in the bottom of water bodies liberation of acids from decomposing organic matter under low O_2 concentration result in low pH. Therefore, the slightly acidic pH in case of the hypolimnetic water (Fig. 5.4a – c) of the present lake throughout stagnation of lake can be related with increased rate of decomposition of the organic matter resulting in conversion of released CO_2 into carbonic acid. A decrease in pH in the lower layers of the stratified lake could also be attributed to accumulation of CO_2, because no light could penetrate through the thermocline to the hypolimnion during the summer period and plants could not consume CO_2 by photosynthesis. Higher values of pH obtained in the epilimnetic waters in the months of June, July, August and September, as illustrated in Fig. 5.4b and 5.4c can be attributed to the effect of photosynthesis, (Goldman and Horne,1983 and Wani and Subla,1990). The present data show a definite pattern in the fluctuation of pH from surface to bottom in relation to the thermal stratification of the lake. A clinograde type of curve of pH was observed and the range of fluctuation from surface to bottom varied from 1.3 – 2.5 units during stratification period, the highest difference in pH being recorded on 2nd June. The pH of the whole water column was almost uniform (Fig. 5.4d) during circulation (December and February). Such a situation has also reported by Yousuf (1979).

Conductivity in water is due to ionization of dissolved inorganic solids and is a measure of total dissolved solids (Bhatt *et al.*, 1999) and salinity. Salts that dissolve in water break in to positive charge and negative charge ions. Koshy and Nayar (2000) observed that the Conductivity value of 250 $\mu S\ cm^{-1}$ is quite normal for aquatic life of freshwaters. According to Crumrine and Beeton (1975) lakes with high conductivity values have greater inputs of ground water and those with conductivity values similar to that of precipitation (14 – 20 μScm^{-1}) receive virtually no ground water.

Relatively lower conductivity values were observed in the epilimnetic waters as compared to hypolimnion, which seems to be due to assimilation of ions by photosynthetic organisms and the mineralization of organic matter under the influence of reducing conditions prevailing in the hypolimnetic water (Motimer, 1941). The mixing of water during circulation results in the prevalence of almost the same conductance values (Fig. 5.5d) throughout the vertical profile of water (Kaul *et al.,* 1980).The CO_2 produced during decomposition results in the conversion of insoluble carbonates lying on the bottom of the lake into soluble bicarbonates.

Dissolved Oxygen reflects the water quality status and physical and biological processes in waters as well as the metabolic balance of a lake (Laluraj *et al.*, 2002). The factors affecting oxygen content in natural waters include atmospheric and photosynthetic input and respiration, decomposition and mineralization of organic matter. DO content is affected by fluctuations in water temperature and addition of sewage waste demanding oxygen (Koshy and Nayar, 2000). Higher DO means rate of oxygen replenishment in water is greater than O_2 consumption and this is healthy for almost all aquatic systems (Adak *et al.*, 2002).

The epilimnion of Manasbal lake was observed to contain about 6 to 8 mg/1 O_2 Fig. 5.6I (a –c), but the hypolimnion exhibited an oxygen deficit ($O_2 < 1$ mg/1) during the stratification period. This oxygen deficit is caused by the high productivity of the lake, depicting meso- to eutrophic nature of lake (Pandit and Yousuf, 2002; Gunkel and Casallas, 2002). The rate of oxygen depletion noticed in the bottom layers of the Manasbal lake are an indication of the more eutrophic nature of the water body.

The present data indicated the varied levels of DO at various depths throughout the study as the content of dissolved oxygen in deep water lakes depends upon the presence and extent of thermocline, which maintains a differential O_2- tension between various strata and at various times of the year (Yousuf,1979). Observed DO values dropped well below the standard limit of 5 mg l^{-1} (Water-research 2006) at the thermocline, leading to the development of anoxia in the hypolimnion during the stagnation period. Bhade *et al.*, (2001) also observed a direct anoxic hypolimnion in the Lake zone extending 25 m down to 45 m in *Tawa r*eservoir. The establishment of anoxic conditions in the hypolimnion can partly be explained by sinking of organic material produced in the epilimnion to the thermocline, where oxidization reduces the DO in the thermocline. The bottom layers of hypolimnion were anoxic throughout the study (Fig. 5.6I c). The anoxic conditions prevailed and the lower layer of thermocline and hypolimnion recorded anoxia upto 19th December as it can be related to the fact that at the last period of stratification anoxia has spread farthest and therefore represents a large part of Anoxic Factor (Nurnberg, 1995).

As the water at lower temperature has greater O_2 retention capability, one would expect a higher O_2 saturation during winter (Sreenivasan, 1972; Vasisht and Sharma, 1975; Zutshi *et al.*, 1978). The present lake showed interesting deviation from this. The higher values of DO were recorded in late winter on 1st February (Fig. 5.6I d). At this time, O_2 is present at all depths as there is complete mixing of the whole water column. The dissolved oxygen higher values were also recorded in April and June (Fig. 5.6I a & b) and is possibly due to higher photosynthetic activity during this period as the macrophytes grows and blooms in spring and summer (Yousuf, 1979).

A typical clinograde curve of O_2 was observed with depth in the present lake, as illustrated in Fig. 5.6(II). The upper water layers remained either above or near the saturation for most part of the study. As illustrated in Fig. 5.7 (I), the water column below 1m was always unsaturated except on 2nd June, when supersaturated condition was recorded upto 3m depth. Wetzel (2001) has related the under-saturated dissolved oxygen in the epilimnion with the presence of humic substances, it seems to be holding true for the present lake as well. With the advancement of stagnation period, oxygen content in the surface layers experienced a fall (Fig. 5.6I c). This phenomenon seems to be related with the deepening of the upper boundary of thermocline which leads to the mixing of O_2- deficient water from the thermocline zone with the upper aerated water of the epilimnion (Stewart and Hasler, 1972 and Yousuf, 1979).

The decrease in dissolved oxygen concentration in the surface layers would correspond to the beginning of water circulation (Rai, 2000). The replenishment of dissolved oxygen in the deep lake on 1st February was caused by infrequent down-welling of cold water that originated from the lake surface (Crawford & Collier, 1997). Another mechanism that can transfer oxygen into deep waters is gravity currents generated by plunging cold water masses due to faster cooling of littoral water during winter (Fer *et al*., 2001). The stratification affects dissolved oxygen and other nutrient concentrations in the water column. The oxycline (the depth of 1mgl^{-1} DO) is around 8 - 9m, thus inhibiting many oxygen-needing organisms from living on the bottom of the lake. With a lower number of organisms, less nutrients are used. Thus, deep waters tend to be nutrient rich. Oxygen depletion initiates a series of reduction reactions that result in dissolution of metal cations from sediments and release of sediment-bound phosphorus (Golterman, 1977).

Waters are grouped into three different nutrient status groups on the basis of alkalinity: (a) 1 to 15 mgl^{-1} as nutrient poor, (b) 16-60 mgl^{-1} as moderately rich, and (c) more than 60 mgl^{-1} as nutrient rich (Sorgensen, 1948; and Moyle, 1949). The total alkalinity varied from 123mg/l at surface on 4th July to 221mg/l at 13m depth on 23rd April (Fig.5.8 a & b). The total alkalinity was found to be highest during the winter months in the surface layers, and lowest during the summer stagnation period in the epilimnion which may be associated with increased population of macrophytes which convert bicarbonates to carbonates and hence reduces the total alkalinity in epilimnion. This assumption is further supported by the fact that free CO_2 gas was absent from June to 8th September (Fig. 5.8 b & c) in the epilimnion. The non-availability of free CO_2 results in the utilization of bicarbonates by plants and release of carbonates most of which (calcium carbonate) are insoluble and hence lost to the water, a process which results in the reduction of total alkalinity. It was observed that with the establishment of thermocline, total alkalinity values in the epilimnetic region decreases resulting in the highest amplitude of variation between the surface and the deeper layers exactly at the time when the CO_2 gas was absent in the surface layers , depicting the presence of carbonates in the surface layers. In the bottom water presence of higher values of total alkalinity is related to the re- entering of carbonates from sediments into the water by conversion into bicarbonates due to the presence of large quantity of free CO_2 concentration in these layers (Ebel and Koski, 1969 and Yousuf, 1979). In winter, when the circulation of water results in the isothermal conditions of water, the total alkalinity values get distributed throughout the water column and results in an increase in surface layers (Fig. 5.8d).

Free CO_2 is essential for photosynthesis and its concentration affects the phytoplankton, and its productivity. The amount of CO_2 in water usually shows an inverse relationship with oxygen (Radhika *et al.*, 2004). With the onset of spring increased photosynthesis accompanied by stratification in the lake, resulted in variations in the carbon dioxide concentration in the three layers. The epilimnetic waters showed the complete absence of carbon dioxide from June to September (Fig. 5.9b & c). It can be attributed to high temperatures which might favour the net autotrophy (CO_2 decrease) mainly in surface waters or photic zones, and net heterotrophy (CO_2 increase) mainly in the deeper layers, where organic decomposition is often higher (Boehrer and Schultze, 2008). The hypolimnetic waters were observed to contain large quantities of carbon dioxide throughout the year as a result of decomposition of organic matter, indicating the productive nature of the lake (Reche and Pace, 2002). In line with the suggestions of Reid (1961), the free CO_2 was almost uniformly distributed throughout the water column when the whole water column was circulating.

Hardness is governed by the contents of Ca and Mg, and the major contribution to hardness is usually Ca. Water with total hardness 0-60 mgL^{-1} is considered soft; 60-120 mgl^{-1} is considered medium and above 120 $mgL^{-1}$is considered very hard (Krishnan, 2008). The total hardness varied from 64mg/l in surface layer on 4th July to 206mg/l at 13m depth on 8th September (Fig. 5.11b &c). The fluctuations in hardness followed those of the Total alkalinity, a condition similar to that observed by Sreenivasan (1972) and Yousuf (1979). The widest range of fluctuation varied between 55- 108 mg/l was recorded during the stagnation period when the concentration increased greatly with depth and the hypolimnion contained large quantities of it. During the winter months, when the water column of the lake was homothermous, the range of fluctuation in total hardness values remained low i. e; 38 – 45mg/l from surface to bottom. On the whole the hardness and alkalinity values for Manasbal lake were found to be very high indicating that the lake gets groundwater from aquifers containing limestone minerals such as calcite and dolomite (Tepe *et al*., 2005). This is substantiated by the fact that main source of water and the lake are the numerous springs spread over its basin.

The calcium hardness values varied from 54 – 125mg/l (Fig. 5.12a – 5.12d) and Mg hardness values from 10 – 81 mg/l (Fig. 5.14a- 5.14d) from surface to bottom in the lake. The higher values of Ca and Mg hardness were recorded in the hypolimnion throughout study. The relatively higher concentration of hardness due to Ca and Mg in the hypolimnion may be ascribed to the presence of large quantities of $CaCO_3$ in sediments. The lake is a typical marl lake (Kaul, 1977) and the carbonates of Ca, in presence of CO_2, get converted into bicarbonates which diffuse into the water. Since the water remained stratified from March to November, the concentration of Ca and Mg hardness in the hypolimnion increased continuously. But when the destratification started the Ca and Mg hardness of the hypolimnion decreased while that of epilimnion increased.

The Ca content varied from 21 to 55mg/l (Fig. 5.13a- 5.13d) from surface to bottom and was recorded quite high as compared to Mg content. It may be partly due to the nature of catchment area which has predominance of calcareous material. The Ca content in the bottom waters was comparatively higher than surface waters. Decrease in the Ca content of epilimnion and metalimnion during summer stratification as shown in Fig. 5.13(b) was observed to be directly associated with the rapid increase in the photosynthetic activity of macrophytes attaining their peak growth and production during the season (Kaul *et al.*, 1980). Similar results were obtained by Otsuki and Wetzel (1974) and Wanganeo (1984). Higher Ca content in hypolimnion may be attributed to dissolution of calcareous materials at the bottom Laluraj *et al.* (2002).

The Mg content varied from 3- 21 mg/l from surface to bottom throughout the study as shown in Fig.5.15 (a –d). The Mg content in the bottom waters was comparatively higher than surface waters. Low Mg content in epilimnion and metalimnion may be due to uptake of Mg^{2+} by plants for the formation of chlorophyll magnesium porphyrin metal complex and in enzymatic transformation. The decline might be also on account by the utilisation of phytoplankton and growing macrophytes.

The chloride content varied from 6.9 – 32.9mg/l from surface to bottom in the lake as shown in Fig. 5.10 (a –d). The chloride content in the bottom waters was higher than surface waters which might be attributed to the presence of decomposed organic matter in the deeper waters.

In natural waters P exists as soluble phosphates, which, when in higher concentration, cause eutrophication of fresh water systems (Rabalais, 2002 and Bandela, *et al.*1999). P enters surface water from human-generated wastes and land run off; domestic waste contains approximately 1.6 kg per person, per year of which 64 % is from synthetic detergents (Kataria *et al.*, 1995). The orthophosphate content in the present lake fluctuated from undetectable values to 133µg/l (Fig. 5.16a – d). The undetectable values were recorded on 7th April, 4th July and 19th December at various depths in epilimnion and metalimnion. In the present lake no definite pattern in the vertical distribution of orthophosphate existed and variations were observed as illustrated in Fig. 5.16 at various depths, the concentration was slightly higher in the deeper layers. Many authors associate the increase in the content to the anoxic conditions present in the hypolimnion because anoxic release from sediment is at least ten times higher than release under oxic sediment conditions (Schernewski,2003) and as per same author, in the centre of the lake, vertical phosphorus concentrations in the sediment show a steady increase between surface and a depth of 50 cm. Primary production and sedimentation cause a decrease in epilimnetic phosphorus concentrations and a strong increase of the concentrations in the anoxic hypolimnion.

Hutchinson (1957) suggests that in lakes with a typical clinograde O_2 curve, a considerable increase in the $PO_4 – P$ may be noticed in the lower hypolimnion in the later phases of stagnation. Mclaren (1967) also recorded a marked increase of phosphate with depth in Ogac lake. On 4th July, the lowest orthophosphate content of the whole year is observed in the uppermost layer upto 2m depth (Fig. 5.16 b). From 5th August the orthophosphate content of the first three top layers down to a depth of 4m increased. This cannot be explained by phosphorus delivery from the hypolimnion. Instead, it could be attributed to the input from the neighbouring agricultural lands. This means that during summer, the agricultural runoff is the most important factor that determines the phosphorus supply in the epilimnion. With the gradual erosion of thermocline the hypolimnetic phosphorus-rich water, mixes with nutrient-deficient epilimnetic water, thereby increasing the concentration. But even on 19th December, the orthophosphate values were found still higher in hypolimnion (Fig. 5.16d), and it might be attributed to the net P-transport from epilimnion to hypolimnion because the upward transport by mixing could overcompensate the downward flux due to sedimentation. In February, the vertical mixing becomes the most important transport process and a net flux upwards into the expanding epilimnion takes place and overall a fall in the ortho-phosphorus was recorded as shown in Fig. 5.16(d).

Elevated NH_4 and PO_4 concentrations are good indicators of inputs from sewage discharge (Xu *et al*., 2008). No definite pattern of fluctuation of total phosphorus was recorded in the vertical distribution in the Manasbal lake and large variations were recorded between different layers (Fig. 5.17). Owing to the anoxic conditions in hypolimnion during summer stagnation, hypolimnetic phosphorus concentration in the lake reached extremely high values (Fig. 5.17 b) due to remobilization of P from sediments (Bluszcz *et al*., 2008) and it could be explained as when oxygen is present, ferric ions (an insoluble form of iron, Fe^{3+}) and phosphates (PO_4^{3-}) form complexes and sink to the sediment so that the phosphate is unavailable to primary producers. Under low oxygen or anoxic conditions, however, the iron is transformed to its reduced state (a soluble form of iron, Fe^{2+}) whereby the ferrous ions and phosphates are released to the water. Another reason could be the decreased flushing rate which will also contribute to the increase of phosphorus concentration in the hypolimnion (Blenckner *et al*., 2002). The variations in the P-content in the epilimnetic layers originates from the contribution of nutrients from inflowing water, and from their loss via the outflow and particulate sedimentation (Salmaso, 2003).

The low ratio of soluble reactive phosphorus to particulate phosphorus in the hypolimnion might be attributed to the presence of phototrophic sulfur bacteria which convert soluble reactive phosphorus into particulate phosphorus. As per Selig *et al*. (2003) part of the released soluble reactive phosphorus in Lake Dudinghausen, was incorporated into the phototrophic sulfur bacteria biomass and thus transformed to particulate phosphorus and resulted in the low ratio of soluble reactive phosphorus to particulate phosphorus in the hypolimnion. The same phenomenon seems to be for water in Manasbal lake.

In natural waters 150 $\mu g l^{-1}$ of nitrogen is a critical value and when the content crosses the limit algal blooms occur (Sawyer *et al.*, 1945). Nitrogen is generally considered the primary limiting nutrient for phytoplankton biomass accumulation (Rabalais, 2002). The forms of N that affect aquatic ecosystems include inorganic dissolved forms; Nitrite (NO_2), Ammonium (NH_4), Nitrate (NO_3) and a variety of dissolved organic compounds such as amino acids, urea and composite dissolved organic nitrogen, and particulate nitrogen. Surface waters generally have lesser NH_4 form than bottom waters because it is liberated often from the decomposing organic matter of the lakes and its release in the deep layers is governed by anoxic conditions (Kaul *et al.*, 1980).

The concentration of NH_4- N in the aerated epilimnetic waters of Manasbal lake is very variable and fluctuated in the range of 9 -127 µg/l, while in the deeper layers, the range was still higher, 99 - 986µg/l (Fig. 5.18 a – d). The minimum values in the surface layers of the present lake were recorded during stagnation period as also recorded by Yousuf (1979) for the same lake. Vertical distribution of NH_4 -N concentration in the Manasbal lake revealed an increase towards bottom. NH_4 -N concentration increased within the hypolimnion of lake throughout the summer stagnation particularly in the month of June, July and September (Fig. 5.18 b & c). This increase is likely the result of anoxic conditions within the hypolimnion as anoxic conditions prevents ammonium oxidation to nitrate (Lewis, 2000 and Havens *et al*., 2003). In surface layers the low NH_4 concentrations result through its utilization by plankton and other plants (Prochazkova *et al.*, 1970). Lower values of

NH_4-N during stagnation period extended upto a depth of 6m, showing irregular fluctuations, an observation in conformity with Yousuf (1979).

From 8m downwards, higher values of NH_4 - N than those of upper layers were also recorded during the stagnation period, as the hypolimnion was observed anoxic. Graetz, Keeney and Aspiras (1973) suggest a net release of N as ammonium-N from the sediments when oxygen concentrations are indetectable. Therefore, levels of ammonium ions increase when loss of oxygen prevents ammonium oxidation to nitrate. In anaerobic hypolimnion where animals are scarce, ammonium is formed at amino-acid degradation of proteins carried out by ammonificating bacteria, occurring in the water column and sediments (Gorlenko *et al*., 1977; Howarth *et al*., 1988; Stolp, 1996) and thus increasing ammonium- nitrogen in the hypolimnion. Maximum values in upper layers were recorded during circulation (Fig. 5.18d), when the whole water column started to mix up as a result of destratification process, with the epilimnetic water (Hutchinson, 1957).

The most important source of NO_3 in waters is biological oxidation of nitrogenous organic matter of both autochthonous and allochthonous origin, which include domestic sewage, agricultural run-off and effluents from industries (Saxena, 1998). The concentration of NO_3 – N fluctuated between 0- 395µg/l (Fig. 5.19 a – d) from surface to bottom in the lake. According to Hutchinson (1957) a dichotomic type of distribution (maximum values in the intermediate depths) is found in productive lakes with a clinograde O_2 curve, due to the removal of NO_3 by assimilation in the trophogenic layer and by reduction near the bottom of the lake. This does not appear to apply strictly to the present lake where inspite of the presence of a clinograde O_2 curve, the NO_3- N profile showed an irregular vertical distribution during the stagnation as well as in early circulation period. The dichotomic type of distribution was observed on few dates, while in others an inverse clinograde depth distribution was evident. The maximum NO_3 – N concentration at various depths was found during the stratification period and lower values were obtained during circulation of the lake which may be attributed to the down-welling of water which caused deep lake water with relatively high concentrations of nitrate-N to up-well into the upper portion of the lake and resulting in the dilution of deeper NO_3 water with the upper layers. Mir (1977) and Yousuf (1979) too has recorded maximum values of NO_3 – N in summer.

With the onset of stratification, it was also observed that from 2nd June to 5th August as illustrated in Fig. 5.19b, concentration of nitrate- N dropped in the hypolimnion and metalimnetic region showed distinct peaks of 176.2 µg/l at 6m depth on 2nd June, 137 µg/l and 132 µg/l at 8m depth on 17th June and 5th August respectively. The reasons for this decrease in hypolimnion is denitrification in the hypolimnion. And the metalimnetic patchiness can be explained by the advection of pockets with residual nitrate from the period of mixis. Similar metalimnetic jet structures were identified in the past during physical studies on internal wave activity in Lake Kinneret (Saggio and Imberger, 2001). With the onset of circulation on 19th December, lowest nitrate concentration were reported at all depths as shown in Fig. 5.19 (d) and this could be related to the fall of D.O concentration throughout water column and it is supported by the increase in ammonium- nitrogen, as not enough oxygen was present for the transformation of ammonia to nitrate (Boyd and Tucker, 1998).

According to Hutchinson (1957) a well marked maximum of NO_2 is to be expected in the hypolimnion at a place where the O_2 concentration decreases most rapidly. In the present lake the NO_2 showed irregular fluctuations at various depths in epilimnion and metalimnion. But the data in hypolimnion revealed well marked increase in concentration throughout stagnation period, thereby showing an inverse clinograde depth distribution. Anigri (1972) and Maulood *et al*. (1978) also found an increase in the NO_2 content towards bottom. During the winter circulation the NO_2 was in the process of mixng up and did not show consistent values at various depths (Yousuf, 1979). The concentrations of NO_2 and NO_3 remained on a low level both in the epi- and hypolimnion.

The amount of dissolved solids or conductivity of a lake is dependent on the lake and watershed geology, the size of the watershed flowing into the lake, the land uses within that watershed, and evaporation and bacterial activity.

The TDS values ranged from 96 – 210mg/l from surface to bottom at different depths during the study period (Fig. 21a- d). The TDS values in the epilimnion were low as compared to hypolimnion which seems to be attributed to the consumption of salt by algae and other aquatic plants, and the rate of evaporation in the epilimnion. As per Lashari *et al*. (2009) the quantity of dissolved salts and temperature greatly affect the ability of water to hold dissolved oxygen and this fact supports the assumption that the hypolimnion has higher TDS values, as the hypolimnion was anoxic during stagnation. The higher concentration of dissolved solids in the hypolimnion could also be attributed to higher concentrations of HCO_3^- , which were largely balanced by equivalent increases in Ca^{2+}, Mg^{2+}, and Fe^{2+} concentrations (Crowe *et al.*, 2008). The higher concentration of HCO_3^- most likely originated from the accumulation of heterotrophic respiration products, but higher concentrations of dissolved Mg^{2+} and Ca^{2+} probably arose from their release during the reductive dissolution of Fe hydroxide carrying phases (Sholkovitz, 1985). Conductivity normally increases in the hypolimnion as bacterial decomposition converts organic materials to bicarbonate and carbonate ions depending on the pH of the water. These newly created ions increase the conductivity and total dissolved solids. For periods, when density stratification limits vertical exchange of water parcels, the supply with dissolved substances is limited (Schwoerbel, 1999 and Wetzel, 2001).

CHAPTER – 7

CONCLUSION

The present investigation enabled a comprehensive and systematic analysis of the physico-chemical characteristics of the water column of the Manasbal lake. The following are the major conclusions derived by the investigation.

Manasbal lake was thermally stratified from March till November, and circulated during winter at temperature > 4^oC. The transparency undergoes a gradual decrease with the advancement of the summer stratification and the least values were recorded at the start and end of stagnation of the lake. A clinograde type of curve of pH was observed and the wide range of fluctuation from surface to bottom varied from 1.3 – 2.5 units during stratification period. Lower conductivity values were observed in the epilimnetic waters as compared to hypolimnion in the present lake during stagnation period and the mixing of water during circulation results in the prevalence of almost the same conductance values at various depths.

The epilimnion of Manasbal lake was observed to contain oxygen content near saturation value, but the hypolimnion exhibited an oxygen deficit (O_2 < 1 mg/1) during the stratification period. The rate of oxygen depletion noticed in the bottom layers of the Manasbal lake are an indication of the more eutrophic nature of the water body. There ocurrs the replenishment of dissolved oxygen in the deep lake layers during circulation period when down-welling of cold water occured that originated from the lake surface.

The total alkalinity values were higher during winter months in the surface layers, and lower during the summer stagnation period in the epilimnion as compared to hypolimnion. The epilimnetic waters showed the complete absence of carbon dioxide from June to September. The hypolimnetic waters were observed to contain large quantities of carbon dioxide throughout the year as a result of decomposition of organic matter, indicating the productive nature of the lake. The free CO_2 was almost uniformly distributed throughout the water column when the whole water column circulated.

During the stratification from March to November, the concentration of Ca and Mg hardness in the hypolimnion increased continuously. But when the destratification started the Ca and Mg hardness of the hypolimnion decreased while that of epilimnion increased. The chloride content in the bottom waters was higher than surface waters.

Stratification of water was found to trap ammonium and phosphates in the hypolimnion during most of the stratification period causing a concentration that is by an order of magnitude higher than in the epilimnion. Therefore, lake was characterised with nutrient-enriched hypolimnion and a nutrient-depleted epilimnion.

On the whole, it may be concluded that the thermal stratification influences the occurrence and distribution of most of the cations and anions in the lake. Consequently, the uptake of these various nutrients by the primary producers, both planktons and macrophytes, is also impacted by the process of stratication in the lake.

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