Lake Léman (Lake of Geneva) was the subject of early limnological studies. Forel published several books (in 1892, 1895, 1904) on the lake

1 Limnology, definition and objective

SUMMARY

The history of limnology has steadily evolved over the last 120 years, both conceptually and technically. Beginning with Forel's classic work on Lac Léman, published in three volumes (1892, 1895 and 1904), and Forbes' classic work on lakes as microcosms (1887), scientific interest in limnology – which encompasses the physics, chemistry and biology of lakes – has continued to grow. Since the early 20th century, research laboratories in many countries in the Northern Hemisphere have continuously promoted limnological research and training of human resources. Initially regarded as the science of lakes, limnology now encompasses **freshwater** and **saline lakes** in the inland of continents, rivers, estuaries, **reservoirs**, wetlands, marshes and all physical, chemical and biological interactions in these ecosystems.

Limnology has contributed significantly to the grounding and expansion of **theoretical ecology**, and modern management of aquatic systems cannot ignore the need for a limnological knowledge base for effective long-term management.

Tropical limnology has advanced through studies undertaken by geographical expeditions and consolidated by research in laboratories in the vicinity of several lake and river systems in Central and South America, Africa, Southeast Asia, and Australia. In Brazil, early limnological studies focused on **fishing**, aquaculture and applied studies in the area of health. In the last 30 years in Brazil, limnology has advanced significantly as a result of studies on several artificial and natural ecosystems, the founding of the Brazilian Limnology Society, the Congress of the International Association of Limnology held in São Paulo (1995), and the relevance of basic research in the management of **water basins**, fishing and lakes, reservoirs and **wetlands**.

1.1 CONCEPTS AND DEFINITIONS

Limnology is the scientific study of all **inland waters** around the world, including lakes, reservoirs, rivers, ponds, swamps, saline lakes and also estuaries and marshlands in coastal regions.

There are several definitions of limnology: Forel (1892) defined it as the oceanography of lakes, Lind (1979) as non-marine aquatic ecology, and Margalef (1983) as the ecology of non-oceanic waters. Limnology and oceanography address parallel problems and processes, as the liquid medium (i.e., the **substrate** water) is common to **oceans**, lakes, and rivers and has certain fundamental properties. Oceans, however, are a *continuum* in space and are much older than inland waters. Inland waters are discontinuous in space, relatively ephemeral (in geological time), and distributed irregularly throughout the inland of continents. The continuity of oceans enables plant and animal species to be more widely distributed. Inland waters rely on the diverse processes of **colonization** and so the diversity and distribution of flora and fauna may be more limited and reduced.

In addition, marine waters, especially oceanic waters, maintain a relatively constant composition of 35–39 grams of salt per kg of water, the main component of which is sodium chloride (NaCl). Inland freshwater as a general rule has at least 0.01 gram of salt per kg of water. The composition of salts varies widely in inland waters. Inland saline lakes in many cases have a much higher proportion of salt than marine waters. Saline lakes occupy a special place in continents. Their ecosystems are unusual and thus are also the focus of limnological studies (see Chapter 15).

Chemical processes and mechanisms occurring in inland waters are highly dependent on the geochemistry of soils in drainage basins. Aquatic systems interact with their drainage basin in various sub-systems and components. That concept and comprehensive studies on drainage basins in relation to lakes, rivers, reservoirs and wetlands are more recent (Borman and Likens, 1967, 1979). The features of water basins determine, for example, the origins of the matter contributing to the formation and functioning of lakes, rivers and reservoirs (see Chapter 11).

Another definition of limnology is from Baldi (1949). He defined limnology as the scientific study of the interrelated processes and methods by which matter and energy are transformed in a lake. He considered the essence of limnology to be the study of movement of matter in a body of water.

In all these definitions, two main aspects must be considered: the descriptive and the functional, along with the necessary synthesis.

The following definition was made as a broad summary:

Limnology is the science of inland waters studied as ecosystems:

- An ecosystem is a natural unit consisting of living components (biotic) and non-living components (abiotic) that belong to a system of **energy flow** and cycling of matter.
- In the structural analysis, two basic aspects are included: first, description of the abiotic components and their properties (**physical** and chemical **factors**, concentrationss and intensities); second, assessment of biotic communities (composition of species, abundance, **biomass** and life cycles).
- Analysis of the interrelated functions in an ecosystem includes research on the elements responsible for the cycling of matter, **dynamic processes** in abiotic

systems, relationships of the organisms to environmental factors and relationships between organisms.

- Limnological research includes analytical field and laboratory research, the results of which may achieve limnological synthesis. Even in studies with limited objectives, realistic connections to the system as a whole should be established. Such studies should contribute to the body of knowledge on the entire system's structure and function.
- Assessment of the practical merits of research in limnology should be made based on detailed analysis of scientific teachings and other knowledge such as basic limnology. A limnologist who acquires experience through his/her own research (individually or in team work) will be better prepared to conduct research and provide interdisciplinary training in limnology. Development and consolidation of research on one of the central topics in limnology should be valued, instead of research on peripheral problems. (Summary based on a presentation made to the International Society of Limnology, 1989, Munich, Germany.)

1.1.1 Contributions of limnology to theoretical ecology

Throughout its history as a science, limnology has contributed significantly to the development of theoretical ecology. Contributions include:

- **Community succession** and factors that control it (studies of **phytoplankton succession**, development of the benthic community in different types on substrata, **periphyton succession**, and succession of **fish communities**);
- **Evolution of communities** (studies on eutrophication in lakes, **restoration** of eutrophic lakes and reservoirs);
- **Community diversity** and **spatial heterogeneity** (studies of periphyton and phytoplankton in different ecosystems, **aquatic insects**, comparative studies on lakes, reservoirs and floodplains. Theory and studies of **ecotones**);
- **Primary production** and energy flow (studies on the primary productivity of phytoplankton, **aquatic macrophytes** and periphyton, **feeding** habits of zooplankton and fishes. Physiological responses of phytoplankton to light intensity and **concentration of nutrients**);
- **Distribution of organisms** and factors that control dispersal and colonization mechanisms (studies on the vertical migration of zooplankton, vertical distribution of phytoplankton, colonization in reservoirs and **temporary waters**, distribution of **aquatic organisms** in lakes, rivers and reservoirs);
- Evolution of ecosystems (studies on **eutrophication**, reservoirs, monitoring reservoirs and alterations resulting from **human activities**).

The contribution of limnology to theoretical ecology took place over a period of approximately 100 years, from early limnological studies and their organization as a science in the final decades of the 19th century. Because of the relative ease of studying organisms, **populations** and communities, the contribution of limnology to theoretical ecology has been invaluable. The paradigm of this contribution can be seen in the summary published by Reynolds (1997) and in the various summaries and hypotheses by Margalef (1998).

1.2 LIMNOLOGY: HISTORY AND DEVELOPMENT

The scope and definitions of any science cannot be considered without looking at the history of its development and the individuals, institutions and groups that have contributed to its progress. This historical overview highlights some pivotal concepts and theoretical trends, as well as theoretical tendencies and basic lines of reasoning employed in many countries and regions. The early history of limnology was described by Elster (1974) and Ueno (1976), with a more recent extension by Talling (2008).

Aquatic organisms attracted the attention of scientists and naturalists in the 17th, 18th and 19th centuries, as can be seen in the works of Leeuwenhoek, Müller, Schaffer, Trembley, Eichhorn, Bonnet, and Goetze. The studies focused on aquatic organisms and their behavior and propagation in water.

With the discovery and early descriptions of marine **plankton** by Müller in 1845, interest in freshwater organisms grew, especially **plankton** in lakes (Schwoerbel, 1987).

The description and measurement of internal **waves** by F. Duvillier and the first descriptions of thermal structure, **wind action** and light penetration in deep lakes by J. Leslie (1838) were important milestones in the progress of limnology (Goldman and Horne, 1983). Also, **diurnal fluctuations** in photosynthetic activities were described by Morren and Morren (1841).

Junge (1885) and Forbes (1887) were the first to treat a lake as a microcosm. In particular, Forbes' work, *The lake as a microcosm* (see Figure 1.1), made a big impact because it highlighted the fact that lakes formed a microcosm in which all elemental forces are at play and the life forms constitute an interrelated complex (Forbes, 1887, p. 537).

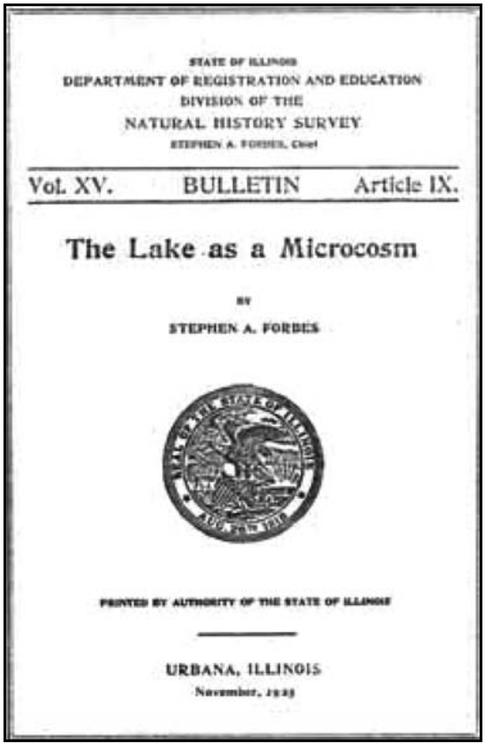
Forbes' work had important consequences that stimulated limnology, but the work of F. A. Forel (1901) was the first synthesis and first book on this science.

In his extensive monograph on Lake Léman (see Chart 1.1), Forel studied the lake's biology, physics, and chemistry, and also formulated original concepts on different types of lakes.

The development of limnology as an organized science began to grow at the end of the 19th century, and already by the early 20th century many limnological field stations and working laboratories had been established near lakes. In 1901, for example, Otto Zacharias founded a limnology research institute in Plön (1981), Germany, which has played an important role ever since (it is now the Max-Planck Institute for Evolutionary Biology).

Subsequent developments in limnology, still in the early 20th century, can be seen in the work of Thienemann (1882–1960) of Germany, and Naumann (1891–1934) of Sweden, who worked independently at first and then together established the first comparative studies on the European continent. The work established an orderly classification, taking into account regional characteristics and **biogeochemical cycles**. The oligotrophic-eutrophic system introduced by these studies, using concepts from Weber (1907), constituted a very important base for advancing the development of limnology. The classification of lakes by trophic status was a first step in the development of this science.

The **typology of lakes** proposed by Birge and Juday (1911) considered the relationships between productivity of organic matter, lake depth, lake morphology and **dissolved oxygen** content.



STATE OF ILLINOIS
DEPARTMENT OF REGISTRATION AND EDUCATION
DIVISION OF THE
NATURAL HISTORY SURVEY
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The Lake as a Microcosm

BY

STEPHEN A. FORBES

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Figure 1.1 Reproduction of the cover of Forbe's study published in Illinois (USA) in 1925 (Vol. XV, Bulletin, Article IX).

Chart 1.1 Books published by F.A. Forel and their contents.

Volume 1 (1892)	*Volume 2 (1895)*	*Volume 3 (1904)*
1. Geography	6. Hydraulics	11. Biology
2. Hydrography	7. Techniques	12. History
3. Geology	8. Optics	13. Navigation
4. Climatology	9. Acoustics	14. Fishing
5. Hydrology	10. Chemistry	

Source: Le Leman. *Monographie limnologique.*

In North America, L. Agassiz (1850) was an early pioneer; essential contributions were later made by Birge (1851–1950) and Juday (1872–1944), who studied the effect of **thermal** and chemical **stratification** on the composition of plankton. They also conducted comparative studies on North American lakes and studied quantities such as water transparency, organic matter and **phosphorus**, developing graphic correlations with frequency distributions and trends (Juday and Birge, 1933). Juday (1916) also conducted comparative studies on several lakes in Central America.

An important difference between the development of limnology in Europe and in the United States is that from very early on, American researchers focused on chemical cycles in systems, while European researchers focused on the study of communities (Margalef, 1983). For example, Birge and Juday used the concentration and distribution of dissolved oxygen to express a set of factors describing the functioning of lakes.

Important events in the development of limnology include the 1922 founding by Thienemann and Naumann of the International Association of Theoretical and Applied Limnology (now called the International Society of Limnology), and the establishment of a laboratory at Windermere (1931) in support of the Freshwater Biological Association, founded in 1929. The association has produced significant works from the lake district in northern **England** (Talling, 1999). In **Japan**, the work of Yoshimura (1938) was important in establishing a scientific information base. An important scientific feature is that many Japanese limnologists have also produced scientific works in oceanography. Japan may be one of the only countries where the boundaries blur between limnology and oceanography, mainly because of the common focus of application in terms of eutrophication studies on inland and coastal waters. Inland, a major focus is on **aquaculture**, which requires thorough knowledge of the major limnological and oceanographic processes – and even a comparative understanding – in order to use common techniques to utilise lacustrine and marine systems for food production.

Research laboratories were also established in the United States and Europe near lakes or regional systems, which basically served as adjuncts to large internationally renowned institutions. The laboratories were active centres that gathered scientific information and conducted research on regional **aquatic ecosystems**. The ever-growing body of research in limnology has contributed to the development of theories, evolution of the science, and greater understanding of regional systems.

Another important factor in this robust and growing science has been the continuing education and training of qualified researchers who across several decades have contributed significantly to scientific advancement in several areas.

Tropical limnology largely advanced through research by groups from temperate regions. As Margalef (1983) points out, an understanding of basic limnological processes should certainly take into account systems in **tropical regions**. In the **Sunda Expedition** in 1928–1929, Thienemann, Ruttner and Feuerborn (Talling, 1996) produced important comparative data, as did the early work of Worthington and of Beadle (1932) in Africa. The work of Thienemann (1931) highlighted the absence of hypolimnetic oxygen in lakes in Java, Sumatra and Bali, and revealed problems in the traditional **oligotrophic/eutrophic** classification used for temperate-region lakes.

The classifications described by Thienemann and Naumann had an important catalytic effect on the scientific development of limnology, and by the 1950s, the classification of lakes had become a fundamental factor. Thienemann (1925) added the term *dystrophy* to the eutrophic-oligotrophic terms to describe lakes with high concentrations of **humic substances**.

In Central and South America, North American and European influences alternated. In South America, major rivers and **deltas** were studied extensively by researchers from the Max Planck Institute (Sioli, 1975) and the National Institute for Amazonian Research (INPA). The Paraná, Uruguay and Bermejo Rivers were studied extensively by Bonetto (1975, 1986a, b), Neiff (1986), and Di Persia and Olazarri (1986).

In Central America, researchers conducted field work during various expeditions to different countries. An early study, already mentioned, was published by Juday (1908). Guatemalan and Nicaraguan lakes were studied by Brezonik and Fox (1975), Brinson and Nordlie (1975), Cole (1963), Covich (1976), Cowgill and Hutchinson (1966). Studies on **Lake Amatitlan** in Guatemala (Basterrechea, 1986) and **Lake Managua** (Lake Xolotlán) in Nicaragua (Montenegro, 1983, 2003) awoke interest in limnology in these two countries. In Chile, limnological studies were conducted at the **Rapel Dam** (Bahamonde and Cabrea, 1984) and in **Venezuela**, limnological studies were conducted by Infante (1978, 1982), Infante and Riehl (1984), and more recently by Gonzales (1998, 2000).

Comparative tropical limnology also developed in Africa, based on numerous expeditions to deep and shallow lakes (Beadle, 1981). Key contributions to tropical limnology were made by studies on **African lakes**, such as **Lake Victoria** (Talling, 1965, 1966) and other lakes (Talling, 1969). Talling and Lemoalle (1998) presented an extremely relevant summary of tropical limnology (see Chapter 16).

More recently, the **International Biological Programme** (IBP) has extensively studied Lake Chad (Carmouze *et al.*, 1983) and Lake George (Ganf, 1974; Viner, 1975, 1977).

IBP was very important for limnology because it allowed the comparison of lakes at different latitudes, the standardization of methods and the quantification of processes. In particular, it encouraged the **study of ecological processes**, enabling a more dynamic and comparative approach. It also established a scientific basis for a more comprehensive quantitative approach in the study of lakes and a comparative study of processes, such as **primary production of phytoplankton** and its **limiting factors** (Worthington, 1975).

IBP summaries promoted innumerable modifications in research methods used to study **primary productivity** (Vollenweider, 1974) and biogeochemical cycles (Golterman *et al.*, 1978), and also stimulated more advanced interpretation of data and correlations between seasonal cycles, hydrological cycles, biogeochemical cycles and primary productivity of lakes, rivers and reservoirs (see Chapter 11).

The evolution of limnology has also been influenced by the construction of large dams (Van der Heide, 1982) in South America and Africa (Balon and Coche, 1974). In Spain, research comparing 100 reservoirs opened huge prospects for the process of classification and **typology of reservoirs** (Margalef, 1975, 1976), mainly focusing on the concept that the study of artificial reservoirs can elucidate the processes occurring in water basins. Margalef's work established an important theoretical and conceptual angle in limnology.

The study of reservoirs differs from the study of lakes, as reservoirs are much younger. They present unique characteristics, with a continuous flow and, in many cases, widely fluctuating levels, reflecting the system's ecological structure. Reservoirs provide the opportunity for important qualitative and quantitative theoretical comparisons with natural lakes (see Chapters 3 and 12).

Figure 1.2 shows the interrelationships between several areas of ecology, limnology, oceanography, hydrobiology and fisheries management, according to Uhlmann (1983).

The wide range of studies in the last 30 years clearly demonstrates the robust and diverse ideas in limnology. The great classic work on limnology in the 20th century

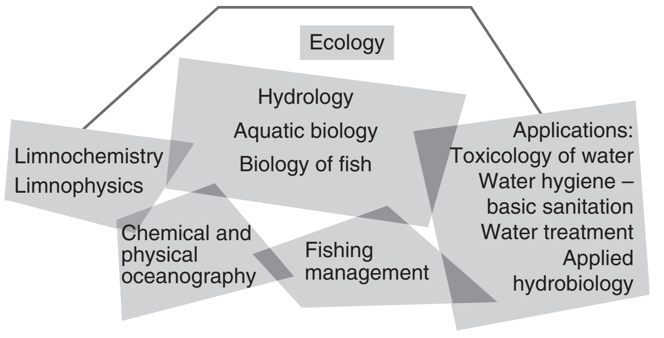

Figure 1.2 Reproduction of Uhlmann's concept (1983) on ecology, limnology, oceanography, hydrobiology, and fishing management, and their interrelationships and applications.

was by Hutchinson (1957, 1967, 1975, 1993). Other classic works influencing scientific research and the training of new researchers include those by Whipple, Fair and Whipple (1927), Welch (1935, 1948), Ruttner (1954), Dussart (1966), Hynes (1972), Golterman(1975),Wetzel(1975),Whitton(1975),Cole(1983),Uhlmann(1983),Stumm (1985) and more recently, Mitsch and Gosselink (1986), Burgis and Morris (1987), Schwoerbel (1987), Moss (1988), Margalef (1983, 1991, 1994), Patten (1992a, b), Goldman and Horne (1994), Hakanson and Peters (1995), Schiemer and Boland (1996), Lampert and Sommer (1997), Margalef (1997), Talling and Lemoalle (1998), Kalff (2002), and Carpenter (2003).

Many works on individual lakes were also published (see Chapter 15).

Chart 1.2 shows the main stages in the development of limnology and the conceptual progress starting with the work of Forel. This is not an exhaustive evaluation but rather it seeks to put into context the major milestones and scientists who introduced the main concepts in this branch of science.

Significant scientific progress in limnology was made during the 20th century. After the descriptive and comparative phase initiated with the development of Thienemann and Naumann's works up until the early 1960s, there was a major breakthrough in knowledge on the processes occurring in lakes, reservoirs, rivers and wetlands. These processes can be summarized as follows:

- Phytoplankton succession and the primary **forcing functions** that define and influence it. **Temporal** and spatial **phases** in phytoplankton succession (Harris, 1978, 1984, 1986; Reynolds, 1994, 1995, 1996, 1997; Bo Ping Han *et al.*, 1999);
- **Transfer of energy**, phyto-zooplankton integration mechanisms and the composition and structure of the **food network** (Porter, 1973; Lampert, 1997; Lampert and Wolf, 1986);
- **Hydrogeochemical** and **geochemical studies** on sediment, **sediment-water** interactions and chemical processes in lakes (Stumm and Morgan, 1981);
- Greater understanding of species distribution, **biogeography**, **biodiversity** and regulating factors (Lamotte and Boulière, 1983);
- Greater scientific knowledge on interactions between aspects of geography, climate, and hydrology and their effects on primary production and biogeochemical

Chart 1.2 Principal developments in limnology and conceptual advances based on Forel's studies.

1901	F.A. Forel	Physical classification based on the **thermal characteristics** of lakes
1911	E.A. Birge and C. Juday	**Chemical classification** based on **stratification** and dissolved oxygen
1915	A. Thienemann	Chemical and **zoological** classification based on balance of oxygen and **colonization of sediments**
1917	E. Naumann	Biological photoautotrophic production in the water column, linked to the concentration of organic material in sediment and balance of oxygen
1932	A. Thienemann and F. Ruttner	The Sunda expedition in Indonesia
1938	S. Yoshimura	Oxygen and **vertical distribution of temperature** in lakes in Japan, comparative analyses
1941	C.H. Mortimer	**Sediment-water interactions**. Circulation in lakes
1942	R. Lindeman	**Dynamic trophic theory** applied to lakes. Introduction of the concept of lakes as functional systems
1952	E. Steemann Nielsen	Introduction of technique to measure primary productivity with radioisotopes (^{14}C)
1956	E.P. Odum	Development of technique to measure **metabolism** in rivers
1956	G.E. Hutchinson and H. Löffler	**Thermal classification** of lakes
1958	R. Margalef	Introduction of the theory of information in the processes of phytoplanktonic succession
1964	R. Margalef	Beginning of studies on the theory of information in the processes of phytoplanktonic succession
1964	IBP	International Biological Programme founded
1968	R.A. Vollenweider	Concept of load from water basins and the effects on eutrophication in lakes
1974	C.H. Mortimer	**Hydrodynamics of lakes**
1974	J. Overbeck	Aquatic and biochemical microbiology
1975	G.E. Likens and Borman	Introduction of the study of the hydrographic basin as a unit
1990	R.G. Wetzel	Interactions between the littoral systems and the **pelagic zone** in lakes
1994	J. Imberger	Hydrodynamics of lakes. New methodologies for calculations in real time
1997	C.S. Reynolds	Summary of the temporal and spatial scales in phytoplanktonic cycles
2004	Goldman, Sakamoto and Kumagai	**Impacts of global changes** on lakes and reservoirs

Source: Various sources.

cycles (Straškraba, 1973; Le Cren and Lowe-McConnell, 1980; and Talling and Lemoalle, 1998).

Two important conceptual frames of reference were presented by Kalff (2002):

- 1960–1970 – Improved measurements of rates and processes, in addition to calculations of abundance and quantity of organisms. Development of **modelling** systems to simulate scenarios and evaluate impact on lakes. Establishment and expansion of the concept of phosphorus loading by Vollenweider (1968). Studies on the transport of nutrients in aquatic systems.
- 1970–2000 – Emphasis on the role of wetlands as functional systems. Re-integration of studies on ichthyology and limnology. Relevant research on **toxic substances**, **acidification** and eutrophication. Surging interest in studying the interactions of structure and function in lakes, rivers, reservoirs and wetland areas.

There was a surge in studies on **aquatic microbiology** and interactions between phyto- and bacterioplankton and phyto- and zooplankton. Concentration, distribution, and fluctuations in the stock of dissolved carbon were extensively studied, as well as temporal variations in DOC and POC (Sondergaard, 1997). The **microbial loop**, already studied by Krogh (1934), was later studied by Pomeroy (1974). Azam *et al.* (1983), in their model of trophic relationships and interactions in the pelagic zone, included bacterial production as an important quantitative process, based on DOC released by phytoplankton and zooplankton. Cladocerans partly play an important role in the food chain because of their ability to graze efficiently on **bacteria**. Key qualitative and quantitative relationships were identified from the dissolved organic carbon, bacterial succession and interactions with zooplankton (Wetzel and Richard, 1996).

During the last several decades, there has been a growing number of studies on distribution, **population dynamics** and biogeography of fish related to chemical composition, **trophic status** and pollution, including studies on **morphometry** and the organizational structure of lakes and reservoirs and the ichthyofauna (Barthem and Goulding, 1997).

As previously mentioned, these advances have had a decisive impact on the formulation of concepts in theoretical ecology and its application.

At the ecosystem level, significant progress has been made in understanding the hydrology of rivers and interactions with floodplain lakes (Neiff, 1996; Junk, 1997); operating mechanisms in wetlands (Mitsch, 1996); comparative studies on reservoirs (Margalef *et al.*, 1976; Straškraba *et al.*, 1993; Thorton *et al.*, 1990), saline lakes (Williams, 1996), interactions between terrestrial systems and aquatic systems (Decamps, 1996), and the ecology of large and small rivers (Bonetto, 1994; Walker, 1995).

Greater understanding of the processes and operating mechanisms at the level of interactions between components of the system or at the ecosystem level gave rise to a large number of contributions on the restoration and management of lakes and reservoirs. Outstanding works include those of Henderson-Sellers (1984) and Cooke *et al.* (1993), and application of models in management and **prediction** of scenarios and impacts (Jorgensen, 1980).

Over the last decade, **biomanipulation** studies on populations have applied scientific knowledge and advances in experimental limnology to the management of lakes and restoration of aquatic systems (De Bernardi and Giussani, 2000; Starling, 1998).

Much progress has been made by studies on shallow lakes (average depth <3 meters), **polymictic** lakes colonized to a great extent by macrophytes and subject to constant oscillations due to fluctuating levels and climatic effects such as wind and solar radiation, with significant interactions between the sediments and water column (Scheffer, 1998).

A discussion on theory and applications, philosophy of the science of limnology and its role in resolving problems was presented by Rigler and Peters (1995).

1.3 TROPICAL LIMNOLOGY

The mapping of the main rivers and watersheds of the continents of South America and Africa was completed in the 19th century.

The major rivers (Nile, Amazon, Zambezi, Niger and **Congo**) were explored and their size and **hydrographic networks** identified. Already by 1910, Wesemberg-Lund had drawn attention to the need for comparative studies on tropical lakes in order to expand the conceptual base. A number of expeditions were undertaken after 1900 (see Chart 1.3) to study biogeography, hydrology and geography. The Sunda Expedition

Chart 1.3 Important ecological expeditions in tropical limnology, in chronological order, 1894–1940.

	Neotropics	*Africa*	*Asia*
1940		Brunelli[16]	
		Cannicci	
–		Morandini	
	Gilson *et al.*[4]	Beauchamp[15]	
1930	Omer-Cooper[11]	Woltereck[18]	
		Damas[14]	
		Cambridge[13]	
–	Carter[3]	Jenkin[12]	Sunda Exp.
	Carter and Beadle[2]	Graham and Worthington[10]	
1920			
–		Stappers[8]	
	Juday[1]	Cunnington[7]	Bogert[17] (Apstein)
1910		Fulleborn[6]	
		Moore[5]	
1900			

The numbers identify the localities and the lakes:
1. Guatemala, El Salvador; 2. Paraguay, Brazil; 3. British Guyana, Belize; 4. Lake Titicaca, the Andes; 5. **Lake Tanganyika**; 6. **Lake Nyasa**, Malawi; 7. Lakes Tanganyika, Nyasa and Victory; 8. Lakes Tanganyika and Moero; 9. Lake Victoria; 10. Lakes Kioga and **Albert**; 11. Ethiopia; 12. Kenyan rift lakes; 13. Kenya, Uganda; 14. Lakes **Kivu**, Edward, and Ndalaga; 15. Lakes Tanganyika and Nyasa; 16. Ethiopia: **Lake Tana**, rift lakes; 17. Ceilão (Sri Lanka); 18. The Philippines, Celebes Islands.
Source: Talling (1996).

(1928–1929) was a major event that brought Thienemann, Ruttner, Feuerborn and Herrmann together for a joint limnological project (Talling, 1996).

A series of expeditions gathered valuable information on tropical lakes and provided a foundation for future long-term research, mainly on African lakes Talling and Talling (1965), Talling (2005) and in the early 1950s on the Amazon (Sioli, 1984; Junk, 1997).

Integrative works on tropical limnology placed more emphasis on the limnology of **large African lakes** and less attention on the tropical limnology of South and Central America. This trend has shifted in recent years, especially due to the growing number of international journals published in South America, putting the contribution of limnologists from tropical regions in proper perspective.

Progress in understanding the functioning of tropical lakes comes from various sources and extensive studies by scientists who have conducted on-going research on many tropical lakes and reservoirs over the last 50 years (Beadle, 1981).

1.4 LIMNOLOGY IN THE 21ST CENTURY

In the last decade of the 20th century, conceptual advances in limnology and scientific investment in the process of discovery led to a significant increase in management and restoration programs for inland aquatic systems. Basic science can decisively support this application. Restoration systems have become more sophisticated, and **ecological models** play an important role in **scenario planning** and preparation (Jørgensen, 1992).

That decade also saw a major breakthrough in technology and development of more precise methods, including automated measurements and real-time data compilation.

The main conclusions that can be reached by analysing the progress of limnology include:

- Knowledge of processes led to the conclusion that lakes are not "freshwater islands" isolated in continents, but depend on interactions with the water basin (Likens, 1992);
- The response of lakes to human activities in water basins varies widely, depending on the morphology and the activities' intensity (Borman and Likens, 1979);
- Lakes respond to the most varied human activities in nearby areas in the drainage basin and also to alterations that occur in distant areas of the basin;
- The accumulation of information by lakes results in responses ranging from physical and chemical processes to community responses reflected in productivity, biodiversity, composition and genetic changes (Kajak and Hillbricht-Ilkowska, 1972; Reynolds, 1997a, b; Talling and Lemoalle, 1998);
- The recognized **complexity of inland aquatic ecosystems** should be the source of ongoing analytical study, integration, and comparison. Each aquatic system in its water basin is unique (Margalef, 1997);
- **Response times** to **climatic factors** and **anthropogenic activities** in water basins vary with the activities' intensity, the characteristics of the ecosystem and the stage of organization (Falkenmark, 1999). Progress has been made in understanding **spatial and temporal stages** in lakes and in response time to forcing functions.

The Sunda Expedition and tropical limnology

The Sunda Expedition took place in 1928–1929 and lasted for 11 months (7 September 1928 to 31 July 1929). The expedition travelled around the lakes, rivers and wetland areas of Java, Bali and Sumatra (now Indonesia). It was led by four researchers: Thienemann, Ruttner, Feuerborn and Herrmann, who traveled extensively throughout the region to make observations, collect biological samples and take meteorological measurements. The limnologists participating in the expedition, particularly Thienemann and Ruttner, were, respectively, specialists in typology of lakes (influenced by the Swedish limnologist Naumann) and in hydrochemical circulation processes and planktonic distribution. The expedition's main areas of focus were the taxonomy of the flora and fauna, stratification and circulation in lakes, and comparison and typology of lakes. A summary of expedition's early results was published by Thienemann (1931).

The Sunda Expedition set a standard for future limnological expeditions in the tropics, especially in terms of biogeography and the ecological characteristics of aquatic flora and fauna in tropical regions in Africa. Other expeditions in Africa followed (Damas, 1937) with the encouragement of the works published by the Sunda Expedition.

Source: Schiemer and Boland, 1996.

For example, spatial and temporal phases in the vertical and horizontal circulation in lakes, reservoirs and rivers seemed to be influenced by several factors, such as basic forces in physical and chemical processes (Imberger, 1994);

- Any progress in managing inland aquatic systems depends and will depend on understanding the operating principles of the systems, and sustainable management will only be possible with **comprehensive management** of the water basin (Murdoch, 1999). The **self-designing capacity** of aquatic ecosystems depends on feedback mechanisms and constant adjustments to structurally dynamic changes (Jorgensen and De Bernardi, 1998).

1.5 LIMNOLOGY IN BRAZIL

Limnology in Brazil developed based on scientific studies that began in the latter part of the 19th century. Oswaldo Cruz (1893) was an important pioneer. Many other observations and early studies of inland and estuarine systems took place in the 18th and 19th centuries (Esteves, 1988). Other contributions to the development of limnology in Brazil arose from medical applications, **microbiology** and the study of fish communities to expand production capacity (fisheries and aquaculture). To lay a solid foundation for aquaculture, it was necessary to better understand the aquatic system, especially natural lakes and reservoirs, and maintain solid conceptual bases for implementation. In this stage of limnology in Brazil, the works of Spandl (1926), Wright (1927, 1935, 1937), Lowndes (1934) and Dahl (1894) played a relevant role.

Esteves (1988) published a detailed description of the evolution of limnology in Brazil, outlining the pivotal points in this science's progress through the 20th century.

Esteves, Barbosa and Bicudo (1995) published a comprehensive summary of the development of limnology in Brazil from its inception up to 1995.

Another significant contribution was made by Branco (1999), who conducted a series of **hydrobiological studies** applying the lessons of **aquatic biology** to sanitation and to the promotion of new comprehensive technologies to coordinate the work of sanitation engineers, biologists and limnologists.

An important milestone in Brazil beginning in 1971 was a set of systematic studies at the UHE Carlos Botelho Dam (Lobo-Broa) and water basin, which introduced many innovative methods for the study of Brazilian aquatic ecosystems. The first publications addressed issues of spatial heterogeneity, horizontal and vertical temperature gradients, distribution of planktonic organisms and phyto-zooplanktonic interactions. Studies were also conducted on fish communities, especially on growth, **reproduction** and feeding, and lake benthos (Tundisi *et al.*, 1971, 1972).

These last studies also focused on **seasonal processes** and established new perspectives to understand interactions between **climatic cycles**, hydrological cycles and the primary productivity of plankton and biochemical cycles (Tundisi, 1977a, b).

The project in this artificial, shallow, **turbulent** ecosystem was also significant because it coincided with the establishment of a human resources training program that led to the inauguration of the graduate program in Ecology and Natural Resources at the Federal University of São Carlos (UFSCar) in 1976. The program enabled the "São Carlos School" to be established in Brazil to train limnologists and ecologists, and it has expanded to a large number of centres of excellence in many regions of the country. Today, limnologists trained at the São Carlos School work in 20 universities and ten research institutes in Brazil and in 15 countries in Latin America and three countries in Africa.

For the education and training of qualified human resouces, not only are there masters and doctoral graduate programs, but 12 international courses on specialized subjects were also offered at São Carlos from 1985–2003, which enabled the training of specialists from Latin American countries, Africa and Brazil. The four initial graduate programs in Ecology in Brazil (INPA – **Manaus;** Unicamp – Campinas; UNB – Brasilia; and UFSCar – São Carlos) had different approaches; UFSCar and Inpa were more focused on aquatic ecology and limnology. Also, the First National Conference on Limnology, Aquaculture and Inland Fishing was held in Belo Horizonte in 1975 (Vargas, Loureiro and Milward de Andrade, 1976).

Over the past 25 years, with the founding of the Brazilian Society of Limnology (1982), the consolidation of limnology conferences and publication of the journal *Acta Limnologia Brasiliensa* (Brazilian Limnology Review), limnology has definitively become established as a science in Brazil. It should also be noted that another milestone was the Congress of the International Association of Theoretical and Applied Limnology held in 1995 in Sao Paulo. That congress was attended by 1065 scientists from 65 countries, with 470 presentations by Brazilian researchers and graduate students, leading to widespread international recognition of limnology in Brazil and numerous interactions in several lines of scientific research that bore fruit after the congress.

The capacity of scientific production in limnology in Brazil can be measured by the growing number of publications, especially in the last 20 years, which has helped consolidate trends, programs and approaches and promote significant progress in the science.

Many summaries and articles have been published in Brazil over the last 30 years. The early and conceptually sound work of Kleerekoper (1944) was followed by the work of Schafer (1985) and Esteves (1988), and summaries produced by Tundisi (1988), Pinto Coelho, Giani and Von Sperling (1994), Barbosa (1994), Tundisi, Bicudo and Matsumura Tundisi (1995), Agostinho and Gomes (1997), Junk (1997), Tundisi and Saijo (1997), Henry (1999a, b, 2003), Nakatami *et al.* (1999), Tundisi and Straŝkraba (1999), Junk *et al.* (2000), Santos and Pires Salatiel (2000), Tundisi and Straŝkraba (2000), Medri *et al.* (2002), Bicudo, Forti and Bicudo (2002), Brigante and Espindola (2003), Thomaz and Bini (2003), and Bicudo and Bicudo (2004).

These recent studies show that limnology in Brazil is undergoing a rapid transformation, shifting away from the simple description of systems and organisms to the interpretation of ecological processes, mathematical modelling, prediction and quantification.

Esteves (1998) published a volume on the ecology of coastal lagoons in Restinga de Jurubatiba National Park and the municipality of Macae (Rio de Janeiro). The work examines the historical, ecological, structural and dynamic aspects of the ecosystems located in the northern part of the state of Rio de Janiero.

1.6 IMPORTANCE OF LIMNOLOGY AS A SCIENCE

The study of limnology is, like other sciences, basically a search for principles. Those principles that are involved in certain processes and operating mechanisms can be used to predict and compare. In particular, the comparative aspect of limnology should be emphasized. For example, when comparing the **hydrodynamics** of rivers, lakes and reservoirs, certain basic functional aspects are immediately understood that affect the **life cycle** and distribution and biomass of aquatic organisms.

This approach, taken by Legendre and Demers (1984), examines the early work on vertical **stability** and instability, phytoplanktonic succession (Gran and Braarud, 1935; Bigelow, 1940) and productivity (Riley, 1942), and in light of recent data on biological variability, sampling and **microscale** techniques, *in vivo* fluorescence (Lorenzen, 1966) and quantifying techniques such as spectral analysis. Other important factors analysed relate to the study of the **physiological behaviour** of phytoplankton and its response to shifting light intensities due to **turbulence**. This new approach views hydrodynamics and its effects on vertical structure as principal controlling factors in phytoplanktonic succession in the system. The approach opens immense theoretical and practical perspectives in the study of limnology, and is one of the advanced points in current limnology, closely aligned with oceanography from the conceptual point of view.

The ability to make predictions and forecasts also qualifies limnology as a science, and is important in applied limnology. In recent years, inland water systems have been increasingly degraded by various types of waste, through deforestation of water basins, and air pollution leading to acid rain. Halting these processes of deterioration and correcting and preventing alterations that damage inland waters can only be achieved if a solid base of scientific knowledge exists.

On the other hand, human interference in aquatic life (overexploitation of aquatic plants and animals, **introduction of exotic species**) has produced many changes in the structure of aquatic ecosystems.

In addition to the problems of pollution, eutrophication, and deterioration that inland waters have suffered, it should be kept in mind that proper management of these ecosystems is also important for better use of existing resources in lakes, rivers and reservoirs. For example, in many countries, construction of dams has significantly modified the structure of natural terrestrial and aquatic ecosystems and introduced new ecosystems with particular characteristics. Management of these systems for diverse purposes represents a considerable investment that should be encouraged, using basic knowledge.

In addition to scientific interest and deepening basic knowledge, limnology can provide important applications.

Another important aspect of the interface between basic and applied limnology is the study of the evolution of lakes and reservoirs. These systems evolved under different types of pressure and the progressive introduction of **ecological filters** that resulted in characteristic mechanisms and the resulting community. This study – which includes aspects of geomorphology, hydrodynamics, composition of the sediment, the ratio of **allochthonous** (externally derived) to **autochthonous** (internally derived) material, and composition of the community – is key to understanding the effects of human activities on inland water systems. Comparisons between lakes of different origins and reservoirs can provide much scientific information needed for understanding ecosystems, as well as for enabling important diagnoses, such as an integrated process of watershed hydrology, extending the concept of limnology to a more global view that not only includes the liquid medium in which organisms live but also the complex system of interactions developed in the terrestrial system around the lake or inland **aquatic ecosystem**.

Figure 1.3 is modified from an original concept presented by Rawson (1939), in which interactions were identified and key objectives in limnology were summarized. The diagram provides an important framework for knowledge on inland aquatic systems. Although other interpretations and processes resulting from further studies will be presented in later chapters, the concepts in the diagram show that a comprehensive and systematic viewpoint already existed in 1939.

The application of basic limnology to the various aspects of **regional planning** is discussed in Chapter 19.

The most important progress in limnology as a science over the last ten years has been the growing understanding of the dynamic ecology of aquatic systems and applications in solving problems of protection, conservation and restoration of lakes.

Another important development in limnology has been the ability to predict the trends and characteristics of lakes and reservoirs over time, especially in terms of controlling influences such as eutrophication and fish stock. The **prognosis** is usually calculated with multiple variables and relatively simple models, based on extensive collection of data.

Utilization of these techniques enables the extensive application of limnology in planning and solving problems, such as those previously cited (see Chapter 19).

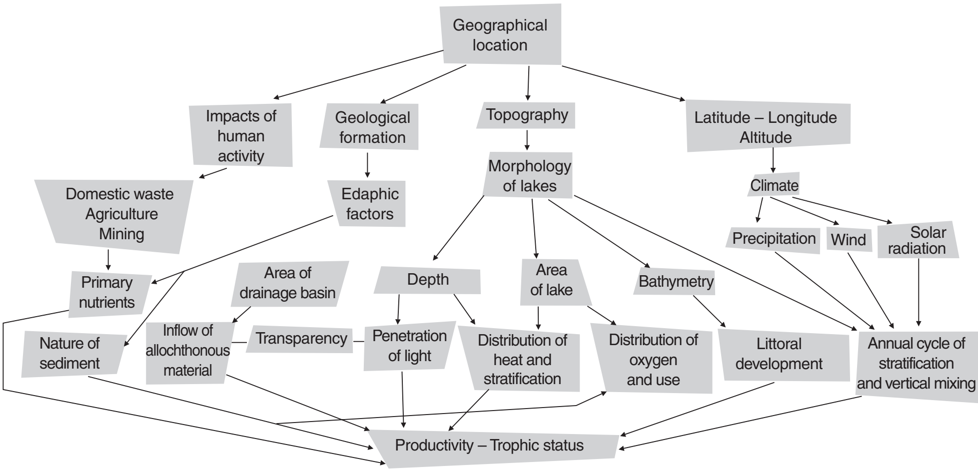

Figure 1.3 Important frameworks in the understanding of inland aquatic systems.
Source: Modified from Rawson (1939).

Chart 1.4 Principal attributes and the hierarchy of factors that act on inland aquatic ecosystems, according to Rawson.

Regional properties	*Climate*	*Geology*	*Topography*	*Retention time of sedimentation*
Characteristics of the drainage basin	Vegetation	Soil	Hydrology	
Attributes and characteristics of the systems	Morphometry	Circulation-stratification		
Physical and chemical properties	Light penetration, Water temperature	Turbidity and **conductivity**	Humic substances	Nutrients Toxins
Biological and ecological properties	Biomass	Productivity	Trophic Structure; Biodiversity	
Impacts of human activities	Destruction of systems and habitats Reduction of biodiversity	Inflow of nutrients and sediments	Climatic alterations	Toxic substances

Source: Based on Horne and Goldman (1994) and Kalff (2002).

Chart 1.4 summarizes **Rawson's concept** and sets out the key attributes and hierarchy of factors involved in inland aquatic ecosystems, including the impact of human activities. The table also consolidates the conception and organization of this work.

Figure 1.4 (Likens, 1992) shows this author's concept of the ecosystem, energy matrix and levels of organization and study based on individuals and communities. The matrix summarizes the current major developments in the approach to and study of aquatic systems, their activities and communities.

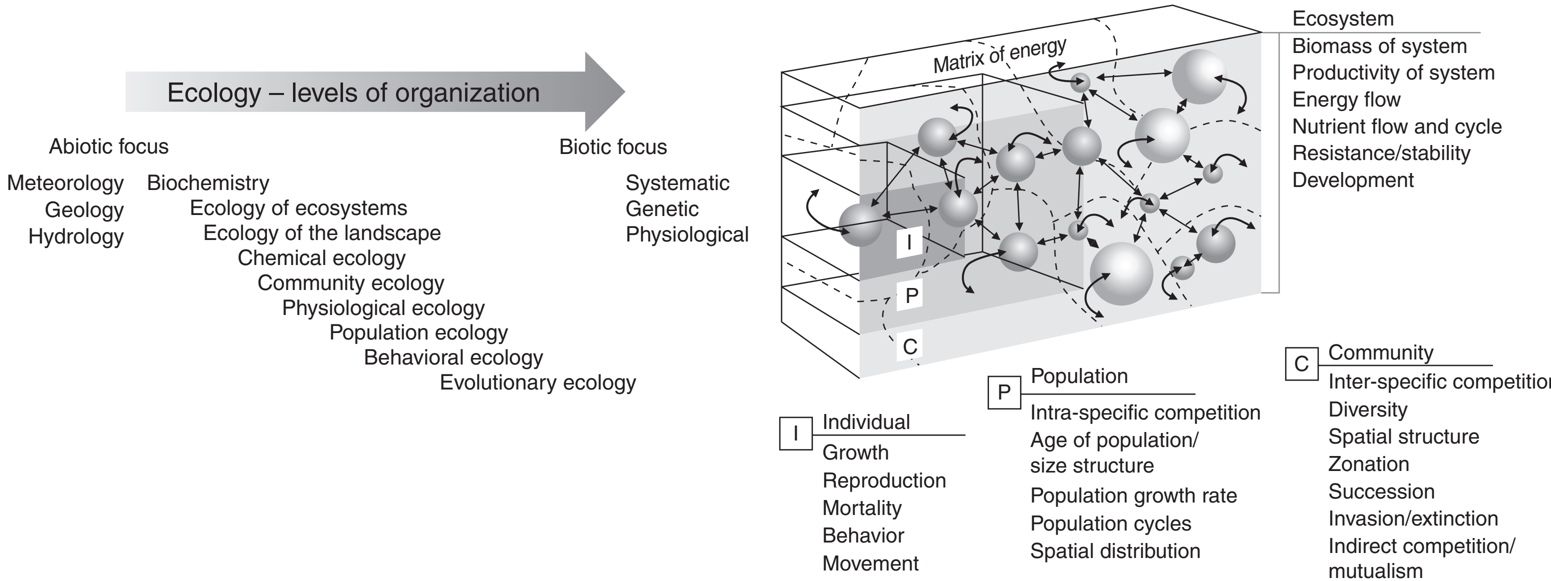

Figure 1.4 Energy matrix of an ecosystem and levels of organization and study based on individual and communities.
Source: Modified from Likens (1992).

Principal scientific publications on limnological studies.

Algological Studies
Amazoniana – Limnologia Et Oecologia Regionalis Systemae Fluminis Amazonas
Ambio
American Scientist
Annals of the Entomological Society of America
Applied Geochemistry
Aquaculture
Aquatic Botany
Aquatic Ecology
Aquatic Ecosystem Health & Management
Aquatic Insects
Aquatic Microbial Ecology
Aquatic Toxicology
Archiv für Hydrobiologie
Archive of Fishery and Marine Research
Australian Journal of Freshwater and Marine Science
Biodiversity and Conservation
Biological Conservation
Biological Invasions
Bioscience
Biotropica
British Antarctic Survey Journal
British Journal of Phycology
Bulletin Ecological Society of America
Canadian Journal of Fisheries and Aquatic Sciences
Conservation Biology
Ecohydrology & Hydrobiology
Ecological Modelling
Ecological Monographs
Ecology
Ecology of Freshwater Fish
Ecotoxicology
Environmental Biology of Fishes
Environmental Conservation
Estuaries
Fisheries Management and Ecology
Fisheries Research
Freshwater Reviews
Freshwater Biology
Hydrobiologia
Hydroecology and Hydrobiology
Inland Waters
Interciência
International Journal of Ecology and Environmental Sciences
International Review of Hydrobiology
Journal of Applied Microbiology
Journal of Coastal Research
Journal of Ecology
Journal of Fish Biology
Journal of Freshwater Biology
Journal of Freshwater Ecology
Journal of Great Lakes Research
Journal of Hydrology
Journal of Lake and Reservoir Management
Journal of Phycology (US)
Journal of Plankton Ecology
Journal of Plankton Research
Journal of Tropical Ecology
Lakes & Reservoirs Research and Management
Limnetica
Limnologica
Limnology and Oceanography
Marine and Freshwater Behaviour and Physiology
Memorie dell' Istituto Italiano di Idrobiologia
Microbial Ecology
Nature
Naturwissenschaften
New Zealand Journal of Freshwater and Marine Science
Oikos
Phykos
Polar Research
Proceedings of the International Association of Theoretical and Applied Limnology
Proceedings of the Royal Society (UK) Series B.
Restoration Ecology
Swiss Journal of Hydrobiology
Water Research
Water Resources Research

In Brazil, the most relevant publications in this area are:

Acta Amazonica
Acta Botanica Brasilica
Acta Limnologica Brasiliensia
Anais da Academia Brasileira de Ciências
Atlântica
Biota Neotropica
Brazilian Journal of Oceanography
Boletim do Laboratório de Hidrobiologia
Brazilian Archives of Biology and Technology
Brazilian Journal of Biology
Brazilian Journal of Ecology

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