General introduction

Surface gravity waves are an ubiquitous feature of lakes and oceans. These waves are initiated by an arbitrary, external disturbance of the water surface (e.g., by wind), where gravity is the restoring force. In natural environments surface gravity waves appear as a unsteady pattern of crests and troughs on the water surface because of the irregularity of wave shape and the variability in the direction and speed of propagation (Fig. I). This is particularly true when the waves are generated by wind. The friction of wind at the air-water interface sets the water surface in motion and generates traveling surface waves. Faster waves overtake and pass through slower ones from various directions. Thus, the observed shape of the water surface is the result of permanent superposition, where waves sometimes reinforce or cancel each other by this interaction (Fig. I).

Fig. I Typically occurring surface wave field generated by wind (Lake Constance).

The first mathematical approaches to describe the phenomenon of surface gravity waves theoretically were made by Airy (1845) and Stokes (1847). Whose theories are referred to as small-amplitude or linear wave theory that generally predicts wave behavior reasonably well as long as the ratio between wave amplitude and wave length as well as water depth are much smaller than one. This implies that the instantaneous depth does not differ significantly from the undisturbed depth. The motion beneath the waves is assumed to be irrotational, ignoring viscous effects of the fluid, the Coriolis force, and density stratification. Linear wave theory is of fundamental importance since it is not only easy to apply, but also reliable over a large segment of the whole wave regime.

The theories by Airy and Stokes were further refined in order to develop adequate and practical solutions for engineering problems, e.g., wave field prediction or coast and harbor protection. Many publications are available that fulfill this purpose by presenting the appropriate theory in accordance with its applications and limitations (e.g., Wiegel 1964; Kinsman 1965; Ippen 1966; CERC 2002). Especially during the last decades, oceanographers have focused on this topic with emphasis on various aspects (e.g., Pond and Pickard 1983; Kundu and Cohen 2002; Duxbury et al. 2003; Garrison 2005). Since linear wave theory provides a reliable description of surface waves in lakes and oceans under most circumstances it is commonly applied and also used throughout this study.

The description of a surface wave involves the waveform at the water surface and the fluid motion beneath the wave. Since the surface profile can be described by a combination of sine and cosine functions, these waves are called sinusoidal or simple harmonic waves. A wave is periodic when its surface profile or motion recurs in equal intervals of time, and is progressive (traveling) when it moves relative to a fixed point whereby the direction in which it moves is called the direction of wave propagation. Further, surface waves have the property to be dispersive, i.e., waves of different wave length or with different frequencies propagate at different velocities. Surface waves are considered oscillatory or nearly oscillatory when the motion of a particle in the water is described by orbits that are closed or nearly closed for each wave period. Taking this into account the wave propagates only energy and not mass.

The most fundamental properties to describe a sinusoidal, oscillatory wave are its length (λ, the horizontal distance between corresponding points on two successive waves), height (H, the vertical distance between its crest and the preceding trough), period (T, the time needed by a wave to travel a distance of one wave length), phase velocity (c, the rate at which the phase of the wave propagates), direction of propagation, and energy (E, total wave energy in the water column per unit horizontal area) (Fig. II). Other more advanced wave parameters are defined by IAHR (1989).

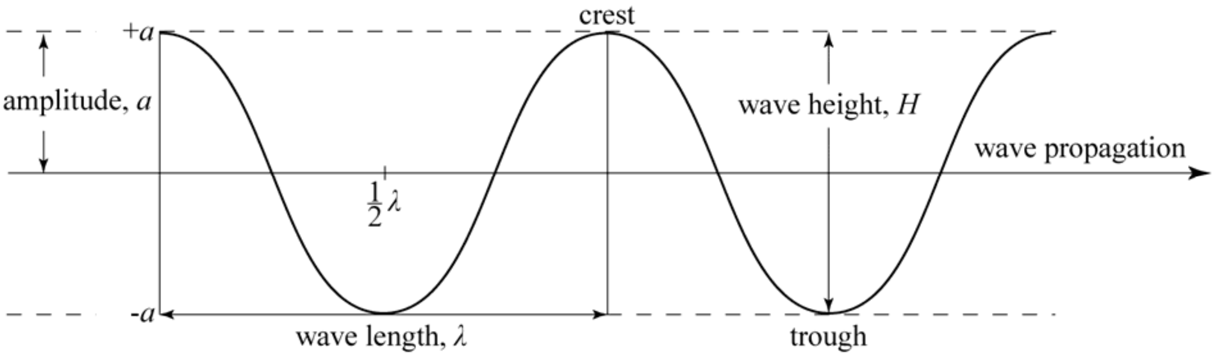

Fig. II Wave nomenclature. Idealized, sinusoidal, progressive wave oscillating around the mean water level.

These wave properties are strongly influenced by the source of forcing, whereby each force generates specific wave properties. The most common way to distinguish waves is by their period or the reciprocal of the wave period, the wave frequency (Fig. III).

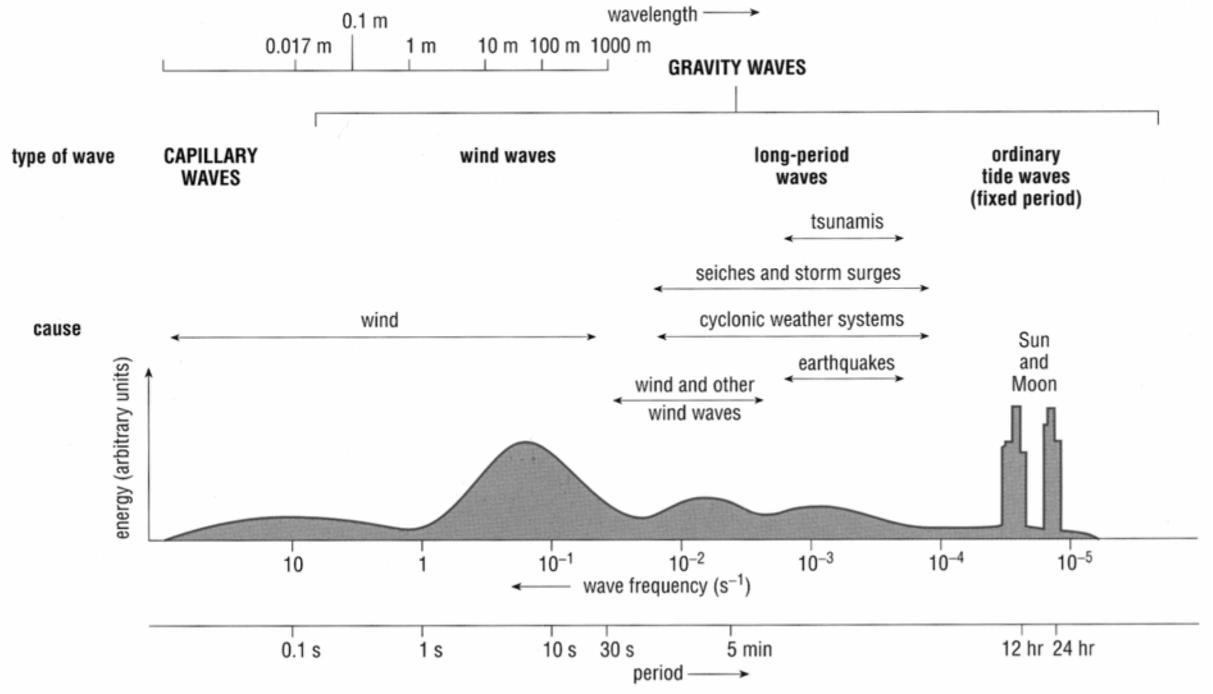

Fig. III Types of surface waves by showing the relationship between wave length, wave period (frequency), the nature of forces that cause them, and the wave energy in the ocean (Brown et al. 2005), after Kinsman (1965).

The illustration in Figure III provides a classification of waves by wave period and frequency ranging from milliseconds (capillary waves) to one day (tide waves). Wind waves have periods of about 1-30 s and form, apart from tide waves, the most energetic part of the wave spectrum.

When waves propagate from the open, deep water into the shallow water they undergo a transformation process due to the interaction with the bottom of the water body. According to the ratio of water depth (*h*) to wave length (*λ*), deep-water, transitional, and shallow-water waves are distinguished (Fig. IV).

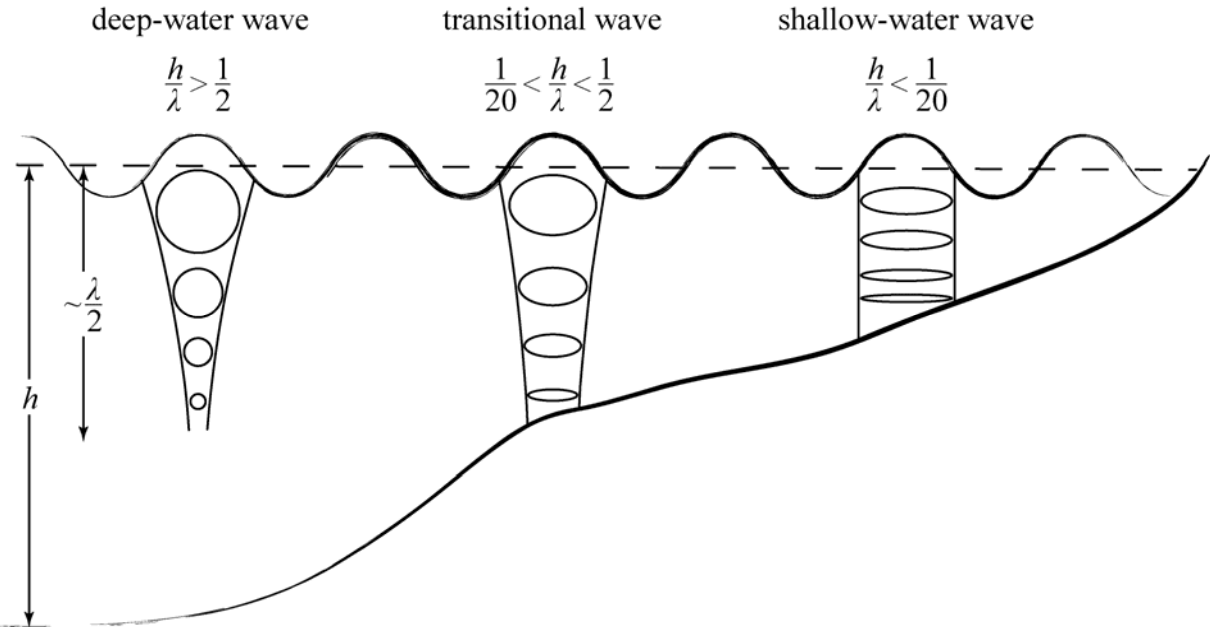

Fig. IV Classification of gravity waves according to the ratio between water depth (*h*) and wave length (*λ*) (adapted from Ippen (1966)). The wave transformation process from the deep into the shallow water alters the associated motion that is expressed in a change of the resulting particle orbits (circles and ellipses). In deep water the particles oscillate on circles (deep-water wave), but with decreasing water depth the wave reaches the point when it starts to feel the bottom (transitional wave). Thenceforward, the orbits flatten in the vertical and particle motion describes an ellipse. This process is further reinforcing, until the minor (vertical) axis of the ellipse vanishes near the bottom and the major (horizontal) axis becomes dominant (shallow-water wave). The cones represent the magnitude and extensions of the particle orbits beneath the wave.

During this transformation process the particle motion beneath the wave, which is in deep water characterized by circular orbits, shifts to elliptical orbits, which flatten further as they reach the bottom. The shallow-water wave is no longer energy dispersive, because their phase velocity is proportional to the square root of the water depth and independent of the wave length. Waves that propagate from deep to shallow waters experience a decrease in phase velocity and wave length with decreasing water depth. Since this study is conducted in the littoral zone, the general wave equations had to be considered that cover the whole range and are not simplified to the specific case (Komen et al. 1996; Kundu and Cohen 2002; Brown et al. 2005).

Many studies deal with the description and investigation of wind-generated waves, but most of these studies are based on investigations in oceans and ocean-shelf regions (e.g., Madsen 1976; Le Blond and Mysak 1978; Dean and Dalrymple 1998). In oceans, waves are generated by strong and frequent winds over long fetch lengths and propagate to the coast with large amplitudes. Typical wave heights vary between 0.5 m during calm sea and several meters during storm events, whereas characteristic wave periods vary between 5 and 10 s (e.g., Komen et al. 1996; CERC 2002; Donelan et al. 2005). On lakes, in contrast, the wind field is mostly characterized by infrequent winds, low wind speeds, and changing wind directions. In addition, the wind forcing at the water surface often varies on small spatial scales and the effective fetch length is restricted to a few kilometers. Hence, the wave field in most lakes is characterized by waves with small amplitudes and high frequencies (short periods) and thus differs considerably from the wave field in the ocean. Wind-generated waves in lacustrine environments have been investigated mainly in the Great Lakes (e.g., Lawrence and Davidson-Arnott 1997; Meadows et al. 1997; Hawley et al. 2004), where the dimensions are rather comparable with ocean-shelf regions. Only a few studies, however, investigated wind waves in smaller lakes (Jin and Wang 1998; Allan and Kirk 2000).

Apart from wind, surface waves can also be generated by ships. The forward motion of a ship disturbs the water around it, resulting in a set of waves with a characteristic pattern. This pattern was first studied and described by Froude (1877) and later by Lord Kelvin (William Thomson 1887). The wash pattern generated by ships in deep water (Fig. V) covers a range of waves in terms of length, phase velocity, and direction of travel. The longest and fastest waves propagate at the same velocity and in the same direction as the ship and are called transverse waves. The shorter, slower waves propagate at a nearly fixed angle of 19.47° to the track of the ship and are called the divergent waves. The transverse and divergent wave components interact at the cusp locus line and result in the so-called Kelvin wedge (Ursell 1960; Sorensen 1973).

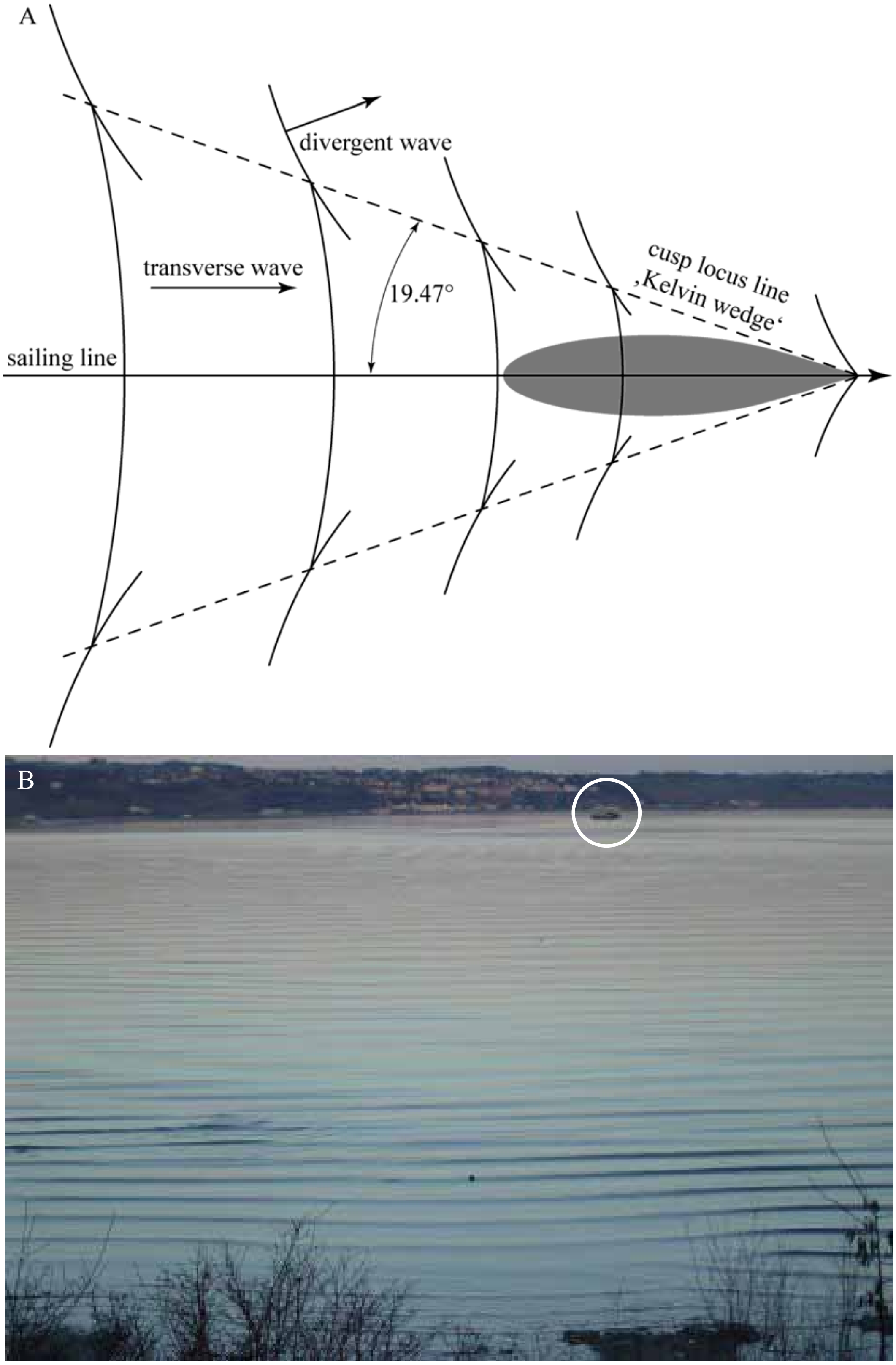

Fig. V Ship waves. (A) Wash pattern generated by ships in deep water (adapted from Sorensen (1973)). (B) Ship waves (divergent and transverse) propagating from their point of generation (sailing line of the car and passenger ferry on Lake Constance, open white circle) over the whole lake into the littoral zone (in the foreground).

During the last decades, many studies were conducted with the focus on a detailed description and simulation of ship waves (mainly carriers) for engineering purposes under consideration of the specific properties of the ships (e.g., length, width, displacement mass, velocity, and shape (e.g., Weggel and Sorensen 1986; Chen and Huang 2004). Several other studies investigated the properties and the importance of regular ship traffic in rivers and channels or ocean-shelf regions (e.g., Sorensen 1973; Stumbo 1999; Bauer et al. 2002), and the relevance of high-speed catamaran ferries in coastal environments (e.g., Parnell and Kofoed-Hansen 2001; Soomere 2005), but, as for wind-generated waves, only a few studies focused on ship waves in lakes (Bhowmik 1975; Maynord 2005).

However, it is particular important to understand and characterize the surface wave field in lacustrine ecosystems too, since surface waves (wind and ship waves) provide an important energy source and thus a hydrodynamic disturbance for the littoral zone, where most of the wave energy is eventually dissipated. Waves are associated with motion in terms of currents of the water column and directly interact with the sediment surface and the benthic biota. Thus, surface waves affect a huge range of abiotic and biotic processes in the littoral ecosystem, such as, resuspension, erosion, and transport of particles (Luettich et al. 1990; Hawley and Lesht 1992; Lee et al. 2007); the release of nutrients and methane (Søndergaard et al. 1992; Güde et al. 2000; Bussmann 2005); the oxygenation of the sediment-surface layer (Precht and Huettel 2003; Precht et al. 2004); the reallocation and stress on benthic invertebrates and their diversity (Rasmussen and Rowan 1997; James et al. 1998; Scheifhacken et al. 2007); the abrasion of periphyton from stones (Cattaneo 1990; Francoeur and Biggs 2006) and aquatic macrophytes (Keddy 1982; Wilson and Keddy 1985; Kawamata 2001); the damage of reed belts (Ostendorp et al. 2004; Schmieder et al. 2004); the light climate via the fluctuations in water level and light attenuation by suspended particles (Stramski et al. 1992; Pierson et al. 2003; Erm and Soomere 2006); and the growth and behavior of juvenile fishes (Stoll et al. 2008).

The central aspects of this thesis are therefore the characterization of the surface wave field in a lacustrine environment and to gain knowledge of its importance for the littoral ecosystem.

The study site is Lake Constance, a large lake, which is located in the southwest of Germany. It is the second-largest (by surface area) prealpine lake in Europe. Lake Constance is not regulated and experiences seasonal water level fluctuations of about 2-3 m (Luft and van den Eertwegh 1991; Jöhnk et al. 2004). The littoral zone covers about 10% of the total surface area (Braun and Schärpf 1990). The shores are mainly exposed to westerly and northeasterly winds, the most and second most frequent wind direction at Lake Constance (Bäuerle et al. 1998). In addition to wind-generated waves, the shores around Lake Constance are exposed to ship-generated waves. These waves stem from ferries with regular sailings throughout the year, passenger ships connecting cities and tourist sites all around Lake Constance, a newly introduced catamaran ferry, and leisure boats. The specific exposure to wind and ship waves of Lake Constance is comparable to many other prealpine and alpine lakes in Europe.

During the last decades intensive biological, chemical, and physical experiments were conducted at Lake Constance (e.g., Fischer and Eckmann 1997; Bäuerle et al. 1998; Scheifhacken et al. 2007). These studies were intensified since the Collaborative Research Center ‘Littoral Zone of Lake Constance’ was established in 1998. During these experiments the different shores were differentiated and characterized indirectly according to their exposure to wind and according to the resulting properties of the shore (e.g., sediment structure and distribution, slope, and occurrence of macrophytes), but not according to the characteristics of the actual wave field. Only one previous study is known, where measurements of the wave field in the bay of Friedrichshafen (Lake Constance) were conducted (Rosenthal 1993). However, technological limitations restricted correct measurements of surface waves to wave heights above 0.3 m, which represents wave heights during strong winds only. Additionally, predictions of the wave field, based on wind fetch and speed, were reasonable but limited by the strong temporal dynamics of the wind and the resulting unsteady wave field (Piroth and Plate 1993). Ship waves were not considered in these studies.

Recent improvements of instrumentation (e.g., pressure sensors) and data acquisition systems allow measuring the water surface elevation very precise, at high frequencies, and over long time periods. This enabled me to measure surface waves during different seasons, wind regimes, and water levels in the littoral zone and to provide a detailed characterization of the wave field including small-amplitude wind and ship waves. In combination with additional measurements I could also determine their implications on physical processes and biological conditions.

In this thesis, I first review different temporal scales of water level fluctuations from a physical perspective (**Chapter 1**). Hydrologically induced water level fluctuations range from days to centuries and are referred to as long-term water level fluctuations. Wind forcing and ship traffic affect the surface wave field and cause water level fluctuations on time scales from seconds to hours. Water level fluctuations are presented in an order of decreasing time scales, beginning with centuries and ending with seconds. This temporal range of water level fluctuations is exemplified using data from Lake Issyk-Kul (Kyrgyzstan) for century scales, the Caspian Sea for decadal scales, and Lake Constance for shorter time scales ranging from years to seconds. Long-term as well as short-term water level fluctuations have specific impacts on the lake littoral ecosystem that are discussed with special emphasis on the importance of the combined effects of both.

In **Chapter 2**, I present an one-year data set on surface wave parameters, which was obtained from the analysis of measurements with a pressure sensor. The data allow for resolving small-amplitude and high-frequency waves. Since the surface wave field in Lake Constance is characterized by wind-generated and ship-generated waves, the purpose of the current study was to analyze and compare their relative importance in terms of frequency of occurrence, wave energy flux to shore, and near-bottom current velocities. This analysis enabled me to identify temporal patterns in the frequency of occurrence of wind and ship waves that result in different patterns of disturbance of the littoral ecosystem.

After the detailed characterization of the wave field and its temporal patterns in Lake Constance, the next step was to investigate potential ecological implications. I concentrated hereby on two effects: the implication on the resuspension of particles and implications on the underwater light climate. To investigate the resuspension of particles (**Chapter 3**), which is highly related to the properties of the surface wave field, synchronized high-resolution measurements of the wave parameters, the near-bottom current velocities, and the suspended sediment concentrations and properties were conducted using a pressure sensor, an acoustic Doppler velocity meter, and sediment traps, respectively. These measurements were analyzed over a time period of one year. Whereas the relative importance of wind and ship waves in terms of the frequency of occurrence was presented in the previous chapter, this study is focused on the different temporal patterns of resuspension, the intensity of disturbance, and the dispersion and reallocation of particles caused by wind and ship waves.

In **Chapter 4**, I experimentally investigated the variability of the underwater light climate in the littoral zone using synchronized, high-frequency measurements of the photosynthetically active radiation and pressure. Fluctuations of the underwater irradiance are not only caused by the variation in the incoming light intensity but also by variations in the elevation and curvature of the water surface resulting from surface waves generated by wind and ships. Synchronized measurements were conducted with the intension of providing amplitudes and temporal scales of the fluctuations in light intensity resulting from wave focusing, the change in surface elevation, and resuspension.

Apart from the field experiments in Lake Constance, I conducted measurements of the surface wave field and the wave-generated currents in the wave mesocosm of the Limnological Institute at the University of Konstanz using a pressure sensor, an acoustic Doppler velocity meter, and a video camera imaging system (**Chapter 5**). These measurements were motivated and required for various biological experiments that focused on the implications of surface waves on biota in the shallow littoral during the last years and also very recently. Additionally, I compared the waves typically generated in the wave mesocosm with wind and ship waves occurring in the field (Lake Constance).

At the end of this thesis, I summarize and discuss the main results drawn from the preceding chapters. Thereafter, I highlight selected questions and perspectives for future research.