Chapter 2
Theoretical Background

2.1 Landslide Processes

2.1.1 Definitions and Classifications

A very basic but widely accepted and used definition for landslide was established by Cruden (1991) and Cruden and Varnes (1996) and defines a landslide as "*the movement of a mass of rock, debris or earth down a slope*". However, the term can be confusing if the parts of the word are considered. Cruden and Varnes (1996) note that it describes all kinds of mass movements and is not limited to granular soil (as land might suggest) or a sliding movement process. The term landslide is well established in the research community and will therefore also be used in this thesis as an overarching term referring to all movement types and material properties. Further on, the term mass movement is used interchangeably with landslide.

The most common classification for landslides is based on material properties and process types (Table 2.1). Besides the main types of movement processes there is one complex class which contains movement processes with two or more different processes acting together along with downslope movement of the landslide mass.

A second widely acknowledged classification of landslides is based on movement velocity (Cruden and Varnes 1996), which ranges from extremely fast to extremely slow (Table 2.2). Moreover, landslides can be distinguished regarding their state of activity. Cruden and Varnes (1996) established eight groups, namely active, suspended, reactivated, inactive, dormant, abandoned, stabilized and relict mass movements. Further on, single, multiple and successive movements are distinguished. Other differentiations can be based on, for example, the water content of involved materials (Cruden and Varnes 1996).

The term creep, which was used to describe continuous and imperceptible slow movements of the ground (e.g., Terzaghi 1950, 1961) was omitted due to various definitions and interpretations. Cruden and Varnes (1996) propose to not use the

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Table 2.1 Mass movement classification based on process type and material (Cruden and Varnes 1996; Dikau et al. 1996)

Process type		Type of material		
		Rock	Debris	Earth
Topple		Rock topple	Debris topple	Earth topple
Fall		Rock fall	Debris fall	Earth fall
Slide	Translational Rotational	Rock slide	Debris slide	Earth slide
Flow		Rock flow	Debris flow	Earth flow
Spread		Rock spread	Debris spread	Earth spread
Complex		e.g., rock avalanche	e.g., flow slide	e.g., slump-earthflow

Table 2.2 Mass movement classification based on velocity of displacement (Australian Geomechanics Society 2002 after Cruden and Varnes 1996)

Class	Description	Typical velocity	Expected damages and population reaction
1	Extremely rapid	>5 m/sec	Disaster of major violence; buildings destroyed by impact of displaced material; many deaths; escape unlikely
2	Very rapid	>3 m/min	Some lives lost; velocity too great to permit all persons to escape
3	Rapid	>1.8 m/h	Escape evacuation possible; structures destroyed
4	Moderate	>13 m/month	Some temporary and insensitive structures can be temporarily maintained
5	Slow	>1.6 m/year	Remedial constructions can be undertaken during movement; insensitive structures can be maintained with frequent maintenance work if total movement is not large during a particular acceleration phase
6	Very slow	>15 mm/year	Some permanent structures undamaged by movement
7	Extremely slow	<15 mm/year	Imperceptible without instruments; construction possible with precautions

term creep and to replace it with the appropriate descriptors of their classification. However, the term creep may still be applied in a simple mechanical way to describe deformation that continues under constant stress (Cruden and Varnes 1996; Terzaghi et al. 1996).

2.1.2 Principles of Slope Stability

Landslides are a sign of slope instability which is defined as the "*propensity for a slope to undergo morphologically and structurally disruptive landslide processes*" (Glade and Crozier 2005b, p. 43). Glade and Crozier (2005b) visualise slope stability as a dynamic spectrum (Fig. 2.1). On one end, there is a stable slope

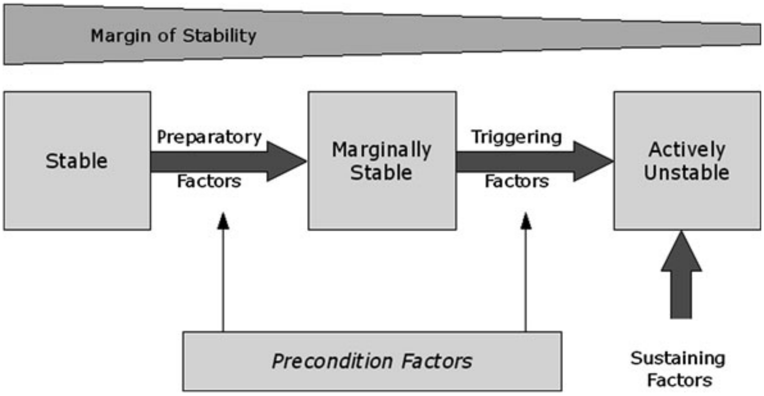

Fig. 2.1 Stability states and destabilising factors (after Crozier 1989; Glade and Crozier 2005b)

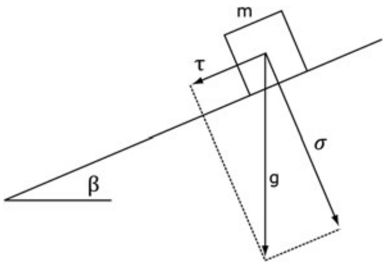

Fig. 2.2 Stress vectors within a slope (after Ahnert 2003)

which is subject to preparatory factors which convert the slope to a marginally stable state. At this point, dynamic triggering factors exceeding certain thresholds can alter the state of the slope to actively unstable which leads to continuous or intermittent movement. During the described transformation from stable to actively unstable slope conditions the margin of stability is continuously decreasing. Precondition or pre-disposing factors are thought as static factors that influence the margin of stability and allow dynamic factors. Preparatory factors are dynamic which change the stability margin over time without initiating slope failure. Typical examples for preparatory factors are weathering, deforestation, tectonic uplift or environmental change. Triggering factors actively shift the state of stability to an unstable condition. Common triggers for landslides are intense rainstorms, seismic shaking or slope undercutting (Glade and Crozier 2005b). Inherent in this concept is the theory of extrinsic and intrinsic thresholds (Schumm 1979). Sustaining factors control the behaviour of the actively unstable state and therefore dictate the duration of movement, form and run out distance of slope failure.

A similar concept is described by Leroueil (2004) who distinguishes four stages of landslide movement: a pre-failure stage including deformation process leading to failure, the onset of failure characterized by the formation of a continuous shear surface through the entire soil mass, a post-failure stage starting from failure until the mass stops, and a reactivation phase when sliding occurs on a pre-existing shear surface.

Stresses acting within a slope can be illustrated by vectors (Fig. 2.2), where a mass (m) is subject to acceleration of gravity (g) which can be differentiated into a downslope component (τ) and a force acting perpendicular to slope surface (σ). Distribution of stresses depends on slope angle (β) and downslope force increases with higher slope angles.

The potentially destructive effects of slope instability led to early research in prediction of slope failures. Calculation of slope stability dates back to Coulomb (1776) and his work on stability of retaining walls and determination of the most likely shear surfaces with a wedge method, which are still valuable today (Ahnert 2003). Another important advance of slope stability calculation was made by Terzaghi (1925), who established the fundamental concept of effective stress. Therein, the effects of pore water pressure in slope stability are acknowledged. Pore water pressure is the pressure of water in the voids between solid particles of the soil (Casagli et al. 1999). As water cannot sustain shear stress, only the skeleton of solid particles at their contact points can, slope stability decreases with a higher pore water pressure. The stability of slope can be assessed by calculating the Factor of Safety (FoS), which is the ratio of driving and resisting forces within a slope (Crozier 1989):

$$FoS = \frac{shear\ strength}{shear\ stress} = \frac{c + (\sigma - u)\tan\varphi'}{\tau} = c + \left(\frac{\frac{W}{A}\cos B - u\tan\varphi'}{\frac{W}{A}\sin B}\right) \quad (2.1)$$

where	τ	=	shear stress
	c	=	cohesion with respect effective normal stress
	σ	=	total normal stress
	u	=	pore water pressure
	σ	=	total normal stress
	σ'	=	$\sigma - u$
	φ'	=	angle of internal friction with respect to effective normal stress
	W	=	weight of the material; that is γ = bulk density multiplied by V
	B	=	angle of shear surface

In theory, a slope is stable as long as the FoS is greater than one and slope movement commences if the FoS is 1.0 or smaller. However, Glade and Crozier (2005b) stress the point that the FoS is only a relative measure of stability as it gives no information on the magnitude of destabilisation that is needed until slope failure occurs. Moreover, some authors describe the onset of movements even before the FoS becomes lower than 1.0 (Petley et al. 2002, 2005b, c) which they

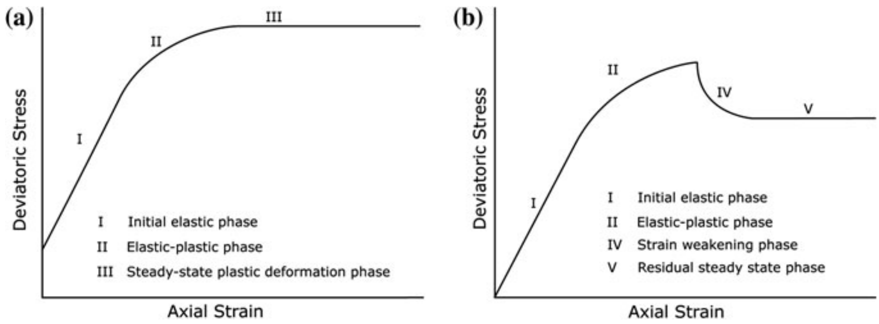

Fig. 2.3 Idealized stress–strain curves for brittle (**a**) and ductile (**b**) deformation (Petley and Allison 1997)

attribute to the development of micro-cracks which progressively form a complete shear surface.

The Mohr-Coulomb equation given above is the basis for limit equilibrium analyses and has been widely applied to calculate the stability of potential slip surfaces. However, in this form it applies to drained failures, where no excess pore pressure is generated during shearing. However, undrained conditions can involve the development of significant excess pore pressure and cause liquefaction, like in the case of low density, fine-grained, saturated soils (e.g., quick-clay) (Bovis 2004). Moreover, shear strength of rock is largely affected by geological bedding and stratification, the properties of involved materials, and the morphology and complex interactions along discontinuities like cracks and joints during shearing (Prinz and Strauß 2006).

Examination of shear parameters and the stress–strain behaviour of materials are primarily experimental, because of the technical difficulties to study the processes in nature. Shear parameters are generally determined in the laboratory by undertaking uniaxial or triaxial shear tests (Wu 1996). A relatively undisturbed soil sample is placed into a shear box and stress is applied until the material fails. Applied loads and subsequent strains are recorded. Idealized stress-strain curves for brittle and ductile failure regimes are given in Fig. 2.3.

Most geological materials and engineering soils can display both brittle and ductile failure modes depending on their confining pressure (Cristescu 1989). However, brittle failure is dominant at low confining pressures representative for shallow failures (Petley and Allison 1997). As stress or load is applied soil materials generally display an initial phase of elastic and recoverable strain. The applied stress is loaded on the grain-bonds within the material which deform but do not break. An increase of stress causes the material's weakest bonds to break and an elastic–plastic phase can be observed which is characterised by increasing strain rates. As more and more bonds break, peak strength is exceeded and shear strength is significantly reduced. The shear surface fully develops in the strain weakening phase in which shear strength steadily reduces to a residual value.

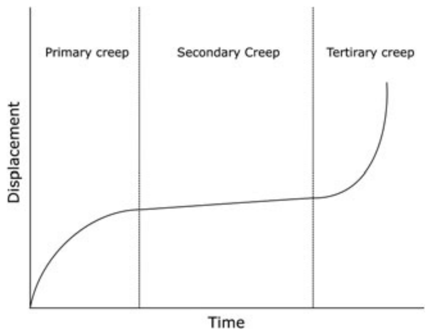

Fig. 2.4 Idealized strain curves for the three stages of creep (after Petley et al. 2008)

During this phase shear zone contraction or dilation may occur which affects pore pressures and therefore strain rates (Iverson 2005). Thereafter, strains primarily occur as displacement along the shear surface.

Ductile behaviour can be observed at high effective stresses prevalent in very deep-seated landslides and in materials with little or no inter-particle bonding like weathered clays (Petley and Allison 1997). The initial phases of elastic and elastic–plastic strain are similar to the brittle failure regime. However, due to the high confining stress no shear surface can develop. Increased load results in purely plastic deformation at constant stresses as the material reforms. Moreover, a transition between ductile and brittle behaviour was observed by Petley and Allison (1997) at very high pressures, which are present in very deep-seated landslides.

As mentioned above the term creep does not describe a certain landslide type but refers to the mechanical behaviour of geological materials to constant stress. Some creep takes place in almost all steep earth and rock slopes and may concentrate along pre-existing or potential slip surfaces or distribute evenly across the landslide profile (Fang 1990). Creep movements in landslide can be continuous or may vary seasonally with hydrological conditions (Petley and Allison 1997). Creep can be maintained for long periods, however, creep gradually decreases shear strength and a slope's margin of stability (Fang 1990) and eventually the slope may fail.

A widely acknowledged concept of creep distinguishes between the phases of creep movement (Okamoto et al. 2004; Petley et al. 2005b, c, 2008). When constant stress lower than peak strength is applied to a soil mass subsequent strains are time-dependant and can be visualised as displacement versus time plot (Fig. 2.4). In the primary creep stage strains are initially high due to elastic deformation but decrease with time. During the secondary creep phase the material suffers diffuse damage but strains are generally slow or almost steady (Okamoto et al. 2004), or may even stop altogether (Petley et al. 2008). When diffuse micro-cracks start to interact to form a shear surface, the critical point into the tertiary phase is reached (Reches and Lockner 1994; Main 2000). This phase is characterized by a rapid acceleration of displacement until final failure.

The increasing displacement rates associated with rupture growth and micro-crack interactions during the tertiary creep stage have been subject to research for a long time in order to predict final failure (Saito 1965; Bjerrum 1967; Saito 1969; Voight 1989; Fukuzono 1990) and volcanic eruptions (Voight 1988). The concept is frequently termed progressive failure analysis and usually employs examination of movement patterns by plotting movement in $\Lambda - t$ space, where $\Lambda = 1/v$ (v is velocity and t is time) (Petley et al. 2002).

It has been observed in many shear experiments and real landslides that linear trends in acceleration occur if failure is imminent. This was the case for first-time failures and for failures in which brittle behaviour was dominant in the basal shear zone. However, reactivated landslides and failures where ductile deformation is dominant display asymptotic trend in $\Lambda - t$ space which has been observed in several landslides, e.g., in Italy, New Zealand, California, Japan and the UK (Petley et al. 2002; Carey et al. 2007).

The potential for prediction and early warning of landslide failures has been showed by several case studies. Kilburn and Petley (2003) and Petley and Petley (2006) analysed displacement data from the famous Vaiont reservoir rockslide in Northern Italy, which caused a flood wave that killed around 2000 people in 1963. The result of the analysis was that at 30 days before final failure a transition to a linear trend in movement acceleration was visible and final failure was therefore predictable. Moreover, in the case of the artificial landslide experiment at the Selford slide (Selford Cutting Slope Experiment) final failure could be predicted 50 days in advance (Petley et al. 2002).

Despite its potential, progressive failure analysis has not been integrated into an early warning system yet. A test application to the slope under investigation in this study failed because of slow movement rates and insufficient acceleration phases (Thiebes et al. 2010).

Slow active landslides are widespread in many geomorphological contexts and materials, and can display steady movements over long periods of time, often along completely developed shear zones (Picarelli and Russo 2004). Changes in displacement rates of slow or extremely slow landslides is in many cases related to varying pore water pressures (Leroueil 2004) and movements can be continuous or intermittent. Especially in landslides of moderate depths pore pressures primarily drive displacements, while in deeper landslides creep and erosion, as other phenomena of stress relief, are the main influential factors (Picarelli and Russo 2004). While pore pressures control landslide movement on short and medium time-scales, erosion, weathering, progressive weakening due to strain are influencing on a larger time-scale (Picarelli and Russo 2004).

Seasonal variations of pore pressures close to surface are not necessarily reflected by deeper layers if materials are rich in clay (Leroueil 2004). Moreover, clays also influence infiltration and slope stability by their swelling and drying behaviour. Very dry clay may develop cracks which allow for quick percolation into depth along preferential flow paths. Preferential flow paths can have a positive effect on slope stability by allowing quick drainage of potentially unstable areas, but can also have an adverse effect by contributing additional water to areas where shear surfaces may develop (Uchida et al. 2001). Infiltration in unsaturated materials is a complex process (Leroueil 2004) and strongly

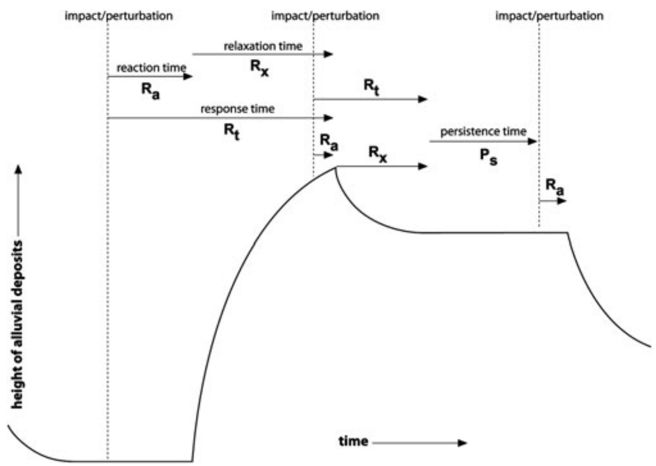

Fig. 2.5 Effects of external perturbations on a geomorphological system (after Bull 1991)

dependant on initial conditions such as antecedent soil water conditions, degree of saturation, pore pressure field, hydraulic conductivity and amount of water required for saturation. As a result, it is extremely difficult to relate rainfall conditions to pore water pressures and to the occurrence of landslides. Moreover, transferring one threshold to an entire landslide is extremely difficult (Picarelli and Russo 2004).

Slow moving slopes often interact with infrastructure as movement rates are generally low, so that permanent avoidance or evacuation is not necessary (Picarelli and Russo 2004). Still there is a danger of acceleration, as many catastrophic slope failures are preceded by long periods of slow creep (Petley and Allison 1997). Geotechnical stabilisation on the other hand would in many cases be too expensive or non-effective.

2.1.3 Systems Theory Considerations

Landslides are the results of complex interaction within the natural environment, and if human intervention is present, the interactions and feedbacks become even more complex (Armbruster 2002). A widely acknowledged approach in physical geography was laid out by Chorley and Kennedy (1971) and aimed to provide a theoretical framework which allows for analysis of form, material, and processes, as well as interaction and feedbacks (Dikau 2005). Moreover, the conceptual approach comprises variable space and time-scales of system evolution and external system control, as well as early approaches to non-linear system response (Slaymaker 1991). Four types of systems can be distinguished: morphological systems, cascading systems, process-response systems and control systems (Chorley and Kennedy 1971).

Following Glade (1997) morphological systems can be used to describe the interaction between landslide-prone regions and potentially landslide-triggering rainfall events. Bell (2007) notes, that if research focuses on, for example, landsliding of periglacial strata cascading systems may be more appropriate. Research on factors controlling landslide behaviour can benefit from a process-response system point of view, while control systems are important in geomorphological hazard research where direct human manipulation of material parameters aims to decrease risks (Dikau 2005). The effects of external perturbation on a geomorphological system are exemplified for alluvial deposits in Fig. 2.5.

Reaction time is important within landslide research and illustrates how fast a slope reacts to external perturbation, such as rainfall, snow melting or earthquakes. Relaxation time describes the velocity of movement until all energy is depleted and may range from slow creeping movements to sudden failure. During persistence time a slope is stable until further perturbation impacts trigger further system response.

The classic systems approach by Chorley and Kennedy (1971) is essentially based on the concept of thermo-dynamic equilibrium which means that a system will return to a steady-state by negative feeback effects after external perturbations (Dikau 2006). In recent years, however, research shifted more to the analyis of non-equilibrium systems and non-linear relationships (Dikau 2005). Nonlinearity implies that "*outputs or responses of a system are not proportional to inputs or forcings across the entire range of the latter*" (Phillips 2006, p. 110), which is dominant in geomorphic systems. Sources of nonlinearity in nature are summarized by Phillips (2003) and comprise thresholds, storage effects, saturation and depletion, self-reinforcing positive feedbacks, self-limitation, competitive relationships, multiple modes of adjustment, self-organisation and hysteresis. Nonlinear system analysis provides, according to Dearing (2004), new insights and aids to understand system behaviour. Novel concepts developed in this area of research include complexity, self-organisation, deterministic chaos and are reviewed and discussed in detail elsewhere (Phillips 1992a, b, 2003; Richards 2002; Favis-Mortlock and De Boer 2003; Dikau 2006).

There is no single, precise definition of complexity (Favis-Mortlock and De Boer 2003). However, complexity may loosely be delineated as the fact that systems cannot be described by the properties of its parts (Gallagher and Appenzeller 1999). According to Phillips (1992a) complexity can arise from cumulative process-response mechanisms which are far too numerous to be accounted for in individual details, or due to multiple controls over process–response relationships that operate over a range of spatial and temporal scales.

The studies of Bak et al. (1988) on sand-pile models provided some insights on complex systems. In these models grains were dropped onto a sand pyramid. This resulted either in no changes, or in landslides of various sizes. The landslide sizes were found to follow a power-law distribution, but it was, however, not possible to predict the size of the next landslide. The fact that the system drove itself to a critical state was referred to as self-organised criticality, a concept that has been

been widely applied to geomorphological processes (Favis-Mortlock 1998; Phillips et al. 1999; Fonstad and Marcus 2003; Favis-Mortlock 2004).

Deterministic chaos describes the sensitivity of a system to initial conditions and small perturbations, whereby initial differences or effects of minor perturbations tend to persist and grow over time and may have unpredictable and apparently random consequences (Phillips 2003). The basic principle of deterministic chaos has popularly been described by the butterfly effect, where the flap of butterfly wings in one part of the world may cause a hurricane at another place. Chaotic behavior was first described by Lorenz (1963) who simulated meteorological processes and found drastically differing model results depending on minimal changes to small decimal places. Prediction of model states was only possible for short time-spans.

These aspects of nonlinearity have drastic consequences for the predictability of natural phenomena such as landslides (Von Elverfeldt 2010). However, this does not mean that prediction is not possible as Dikau (2005) notes: nonlinear systems can be simple and predictable, but this is not necessarily the case for complex systems. Most landslide simulation programs, such as the models presented in Sect 1.3, cannot accomodate nonlinear system behaviour, such as complexity, self-organisation or deterministic chaos. Some landslide related research projects, however, exploited for example self-organised criticality for prediction of landslides and forest fires (Turcotte and Malamud 2004), characterisation of landslide evolution (Huang et al. 2008) or analyis of triggering conditions (Stähli and Bartelt 2007). Moreover cellular automata have widely been used to simulate self-organising complex systems in geomorphic research (Smith 1991; Avolio et al. 2000; D'Ambrosio et al. 2003; Iovine et al. 2005; Fonstad 2006).

2.1.4 Landslide Triggering

Even though landslides can occur without the impact of external factors, generally their occurrence is connected to some kind of triggering event. Many factors can act as triggers for landslides. The most common natural triggers are either related to geological events, such as seismic shaking due to volcanic eruptions or earthquakes, or hydrological events such as intense rainfall, rapid snow melt or water level changes in rivers or lakes at the foot of slopes (Wieczorek 1996). Moreover, human interaction in the form of loading or slope cutting can trigger landslide events. The most important trigger, however, in both shallow and deep-seated landslides is intense rainfall (Crosta and Frattini 2008). Infiltrating rain percolates within the soil, thus increasing pore pressures at hydrologic boundaries, which subsequently decreases shear strength. Positive pore water pressure may occur directly caused by infiltration and percolation (saturation from above), or may be the result of perched groundwater tables (saturation from below) (Terlien 1998). Important factors determining the evolution of saturation are soil permeability and stratification, preferential flow paths, as well as mechanical characteristics (Berardi et al. 2005).

In the following landslide triggering, the efforts made to predict landslide occurrences with respect to hydrological thresholds will briefly be described. More general reviews on landslide triggering (Wieczorek 1996; Schuster and Wieczorek 2002; Wieczorek and Glade 2005) and rainfall threshold determination (Terlien 1998; Wieczorek and Guzzetti 1999; Polemio and Petrucci 2000; Aleotti 2004; Wieczorek and Glade 2005; Guzzetti et al. 2007; Guzzetti et al. 2008; Brunetti et al. 2010) can be found in the respective literature.

Prediction of landslide triggering thresholds is one of the key issues in landslide research (Berardi et al. 2005), and established thresholds have an important role in early warning (Terlien 1998). One of the most influential works in this field was published by Caine (1980) who worked on landslide triggering rainfall thresholds based on rainfall intensity and duration analyses. Since then, many research projects worked on defining rainfall thresholds which trigger landslides. Triggering thresholds are predominantly expressed as rainfall intensity and duration, or cumulative and antecedent rainfall, and can be defined as the line fitting the minimum intensity of rainfall associated with the occurrence of landslide in different areas (Caine 1980). However, Terlien (1998) notes that rainfall events that did not cause landslides also should be recognised. Therefore, minimum and maximum thresholds should be acquired, where rainstorms below the minimum threshold never cause landslides, and storms above maximum threshold always lead to landslides (Glade 1998; Crozier 1999). Between these thresholds landslides may occur under certain conditions.

Landslide triggering thresholds differ from one region to another based on hydro-climatological and geophysical properties, such as regional and local rainfall characteristics and patterns, slope morphometry, soil characteristics, lithology, morphology, climate and geological history (Crosta 1998). Further on, landslide triggering thresholds may also vary with time (Crozier 1999), for example due to seasonal changes of vegetation (Wieczorek and Glade 2005). Moreover, Crozier and Preston (1999) note that after movements have occurred resistance to further events may occur, if for example., all material for future debris flows has already been transported.

Guzzetti et al. (2007) distinguish between rainfall thresholds on three spatial scales, for example, global, regional and local scale. A further distinction between landslide triggering rainfall thresholds can be made between statistical or empirical and deterministic thresholds (Guzzetti et al. 2007). When sufficient data on landslide occurrences and rainfall conditions are available, thresholds can be determined in a statistical way. With limited data deterministic models have to be applied to predict landslide behaviour under certain hydrological conditions (Terlien 1998).

Most case studies of rainfall thresholds relate to shallow landslides or debris flows. Triggering of these landslide types generally refers to short and intense rain storms, while the occurrence of deep-seated landslides is more affected by long-term rainfall trends (Terranova et al. 2007). Deep-seated landslides share a more complex hydrology compared to shallow landslides and simple correlations between rainfall and deep-seated landslide triggering cannot be determined (Terlien 1998). To establish triggering rainfall thresholds in deep-seated landslides it is necessary to include rainfall, water infiltration and percolation, generally by means of modelling subsurface hydrology (Ekanayake and Phillips 1999), and to determine the location of shear surface, as well as the hydrological triggering mechanism (Terlien 1998).

The intensity-duration method first proposed by Caine (1980) has been applied in many other studies (Pasuto and Silvano 1998; Jakob et al. 2006; Matsushi and Matsukura 2007; Crosta and Frattini 2008; Guzzetti et al. 2008; Capparelli et al. 2009; Saito et al. 2010). Rainfall duration generally refers to periods between 10 min and 35 days (Guzzetti et al. 2008), but some authors extended the time span analysed to several months (Terranova et al. 2007; Marques et al. 2008). Long-term rainfall trends have been integrated into threshold determination by relating intensity and duration of rainstorms to mean annual precipitation (MAP) (Giannecchini 2006; Giannecchini et al. 2007; Guzzetti et al. 2007; Sengupta et al. 2009).

Crozier and Eyles (1980) developed the Antecedent Daily Rainfall method to determine rainfall thresholds based on antecedent and daily rainfall. A decay factor derived from discharge hydrographs controls the influence of antecedent soil water. Several other case studies applied this methodology as well (e.g., Crozier 1999; Glade 2000; Glade et al. 2000; Strenger 2009).

Although rain is regarded as the prime factor of landslides triggering, infiltration and the development of positive pore water pressures at potential shear surfaces are initiating landslide processes (Reichenbach et al. 1998; Ekanayake and Phillips 1999; Leroueil 2004). There is, however, no established standard procedure for calculation of pore pressure in relation to rainfall events (Persson et al. 2007). A common procedure is to calculate pore pressures conditions required for slope instability which are then compared to observed pore pressures and checked for reasonability. Based on multiple regression analysis of piezometric measurements Matsushi and Matsukura (2007) established rainfall intensity duration thresholds. Godt et al. (2006) applied a similar approach and derived rainfall thresholds by comparing rainfall data with measurements of volumetric water content. Other authors utilise models to predict pore pressure in response to rainfall events. Wilson (1989) presented a simple numerical model to investigate the build up of saturation and establish rainfall thresholds. The model represents soils as leaky barrels, where additional water is added at one rate, while water is lost by another rate. Wilson and Wieczorek (1995) combined the model with measurements of piezometric levels and data on antecedent rainfall to derive rainfall thresholds. A related approach has been performed by Terranova et al. (2007) who derive critical rainfall situation for landslide triggering based on modelled infiltration and comparison with piezometer data. Moreover, several other case studies also applied hydrological models to predict pore pressure evolution in response to rainfall events to establish landslide triggering rainfall thresholds (Reid 1994; Crosta 1998; Terlien 1998; Ekanayake and Phillips 1999; Iverson 2000; Frattini et al. 2009).

Coupled hydrology and stability models have been widely applied to predict the effects of rain storms, and to define critical situations. Examples for local scale (Buma 2000; Brooks et al. 2004; Berardi et al. 2005; Pagano et al. 2008), and regional scale (Dhakal et al. 2002; Crosta and Frattini 2003) approaches can be found in the respective literature.

2.2 Landslide Investigation and Monitoring

The occurrence of landslides is sometimes surprising for humans as they seem to occur without previous warning signs. However, (Terzaghi 1950) noted that if a landslide comes as a surprise to eyewitnesses, it would be more accurate to say that the observers failed to detect the phenomena which preceded the slide. Therefore, dedicated landslide analyses and monitoring methods have to be applied to be able to recognise potential slope failures.

Many methodological approaches have been developed to reveal the occurrence of landslides in space and time, to investigate processes acting within mass movements and to monitor ground displacements. The wide range of possible methodological approaches for landslide research stretch from field or desk-based mapping, to measurements of surface and subsurface movement in field or by remotely acquired data sources, recordings of triggering factors like rainfall or hydrological parameters, and the use of simulation models.

Landslides can be assessed on various spatial scales (Glade and Crozier 2005a), but a general distinction between local and regional approaches can be made. The initial step of regional approaches is to define the spatial occurrence of landslides, commonly by preparing landslide inventories (Wieczorek et al. 2005). For local analyses Nakamura (2004) argues that one of the first steps to understand the landslides under investigation are field investigation s and boreholes to define the slip surface. Regarding rockslides, but also applicable to other landslide phenomena, Glawe and Lotter (1996) stated that when instabilities can be expected geotechnical investigation s, displacement monitoring and modelling techniques are generally applied. Following Cornforth and Mikkelsen (1996) ideal features of a landslide monitoring system are continuous measurements of pore water pressure in the shear zone by automated sensors in order to correlate these with rainfall data.

In the following a review of methods for landslide detection, surface and subsurface investigations and monitoring techniques is given. The aim of this chapter is not to provide a complete summary of all methods available for landslide research, but rather to give a comprehensive overview on the methods most used in research practice and to highlight their advantages and disadvantages for monitoring. More information on the methodological approaches to landslide investigation and monitoring methods can be found in the sources given or in the general reviews (Franklin 1984; Keaton and DeGraff 1996; McGuffey et al. 1996; Mikkelsen 1996; Soeters and Van Westen 1996; Turner and McGuffey 1996; Olalla 2004; Van Westen 2007; Liu and Wang 2008). No self-contained review on existing monitoring systems will be given as many examples of monitoring systems are presented in the review on early warning systems (Sect 1.4). It is however important to mention that many landslide monitoring systems employ several different techniques, such as methods for measuring landslide movement and hydrology.

Regarding monitoring it should be made clear, that there is no obvious threshold that determines what time intervals between repeated measurements are necessary for it to be classed as monitoring. Olalla (2004) points out that monitoring can range from, for example, inclinometer measurements carried out once in a year, or automatic measurements in intervals of seconds. Therefore, every repeated measurement could be defined as monitoring. Automatic monitoring systems are however more convenient than manual measurements as they do not require humans to regularly go to study sites which may be remote or difficult to access. Another advantage of automated monitoring systems is the ability to control measures by time intervals, thresholds or user input. Besides this, questions of data storage, transmission and security arise with such automatic systems. Moreover, data should automatically be processed and checked to prevent inconsistencies (Olalla 2004). However, issues of managing automatic monitoring systems will not be discussed here.

2.2.1 Mapping and Inventory Approaches

A basic method to detect landslides in space and to prepare landslide inventories is geomorphological mapping in the field. Geomorphological mapping requires expert knowledge and experience of landslides and the study area. Results can vary drastically depending on the specialists who prepared the map, the knowledge on the study area and the processes present (Guzzetti et al. 2000; Ardizzone et al. 2002). Repeated mapping campaigns in the field without further measurements give rather qualitative information on how processes have evolved over time but are essential for process understanding. Important information could include cracks that open up due to ground displacements, or damage to existing infrastructure.

Landslide maps and inventories are frequently prepared based on the analysis of remote sensing data like stereographic aerial or space-borne images, and digital terrain models (DTM) from, for example, LiDAR (Light Detection And Ranging) data. General reviews on landslide mapping and inventories can be found in various literature sources (e.g., Soeters and Van Westen 1996; Malamud et al. 2004; Guzzetti et al. 2006; Van Westen 2007).

The use of aerial photography is well established in landslide research (Soeters and Van Westen 1996). Interpretation of aerial images is primarily qualitative;

however photogrammetric methods can be used to extract quantitative information. While qualitative interpretation is common, quantitative studies are more rare, probably due to limited availability of good quality photographs, adequately fixed control points and cost (Morgenstern and Martin 2008). However, several landslide related quantitative photogrammetric studies have been described (Maria et al. 2004; Mills et al. 2005; Hu et al. 2008; Liu and Wang 2008; Smith et al. 2009).

Medium resolution satellite imagery, such as LANDSAT, SPOT, ASTER, IRIS-D etc., is today used routinely to create landuse maps and inventories of landslides (Van Westen 2007). He also notes that Google Earth and other providers of high resolution satellite data greatly facilitate mapping by offering capabilities of creating polygons and exporting them to Geographic Information Systems (GIS). In several case studies landslide inventories were created based on satellite imagery (Mondini et al. 2009; Fiorucci et al. 2010; Santurri et al. 2010; Yang and Chen 2010) or Google Earth (Sato and Harp 2009; Chigira et al. 2010).

In recent years the interpretation of Airborne Laser Scanning (ALS) DTM data has been frequently applied for creation of landslide inventories (Van Westen 2007). By removing vegetation and other objects from the DTM, Digital Surface Models (DSM) can be created (Schulz 2004). This together with different modifiable angles of shading enable very detailed mapping of landslides and other geomorphological features (Haneberg 2004; Thiebes 2006). Examples of ALS-based landslide maps are provided by several authors (Chigira et al. 2004; Sekiguchi and Sato 2004; Ardizzone et al. 2007; Eeckhaut et al. 2007).

By using multi-temporal remote sensing data sets landslides can be dated, and activity and evolution quantitatively investigated. Examples for multi-temporal landslide inventories are provided by several authors (e.g., Cardinali et al. 2002; Dai and Lee 2003; Brennecke 2006; Imaizumi et al. 2008; Chiang and Chang 2009).

Several automatic landslide detection and mapping approaches have been developed and are comprehensively reviewed by Van Westen (2007). These approaches utilise DTM subtraction analysis or multi-spectral analysis of satellite imagery. Fairly recent applications of an automated landslide mapping system are presented by Tarantino et al. (2004) and Booth et al. (2009).

Another remote-sensing method for mapping landslides and for detection rates and extents of ground deformations is Synthetic Aperture Radar (SAR). SAR and the related methods of Interferometric SAR (InSAR), and their use for landslide research are extensively reviewed by Rosen et al. (2002), Froese et al. (2004) and Morgenstern and Martin (2008). SAR is based on microwave signals which are emitted by a satellite or airplane and the back-scattered signals, which represent distance measurements, are recorded. By processing two slightly offset images from the same flight paths InSAR images can be created which can be used to create pixel-based images which form a DTM. The benefits of this method are that radar measurements can be performed at almost every weather condition and at day and night. Furthermore, large areas can be analysed in a short period of time. Determination of displacements can be achieved by analysing images from different flights. To further increase the accuracy of displacement measurements Permanent or Persistent Scatterer Interferometric Synthetic Aperture Radar

(PS-InSAR) was introduced to landslide research (Morgenstern and Martin 2008). Permanently fixed ground-points, in many cases buildings or other constructions, are determined in multiple InSAR images and relative movements of these points can be measured. Best results, with accuracy of measurements in the sub-centimetre range, can be obtained for movements along the line of sight (Rosen et al. 2002; Luzi et al. 2005). Several case studies have been performed utilising satellite-based InSAR technology to detect and monitor ground movements (Colesanti and Wasowski 2004; Ferretti et al. 2005; Meisina et al. 2006; Calcaterra et al. 2008; Vallone et al. 2008; Yin et al. 2010b).

Also historic data such as newspaper articles, eyewitness records, road construction office reports, city archives, old photographs and many more sources can be utilised for landslide mapping. In many cases spatial and temporal information regarding landslide occurrence can be found which are exceptionally useful for understanding the magnitude-frequency characteristics of mass movements (Glade 2001). Examples of landslide inventories based on historic data can be found in, for example, Calcaterra et al. (2003), Carrara et al. (2003), Tropeano and Turconi (2004) and Kohn (2006).

2.2.2 Displacement Measurements

Many field methods exist to measure ground displacements due to landslide movements. A simple but convenient field method is the use of quadrilaterals (Keaton and DeGraff 1996) which consist of four stakes that are fixed inside and outside the landslide body. Distances between the stakes can then be measured manually by tape. Quadrilaterals have been applied within several research applications (Baum and Fleming 1991; Bogaard 2000; Giraud 2002; Fernandez Merodo et al. 2004; Keaton and Gailing 2004).

Standard theodolite geodetic measurements are frequently applied to measure and monitor ground displacements (Reyes and Fernandez 1996; Walstra et al. 2004; Wasowski et al. 2004; Burghaus et al. 2009) and available automatic systems have often been used (Oboni 2005; Heincke et al. 2010). However, theodolite measurements require pre-defined ground points or prisms. Manual measurements are also cost and time intensive.

The Global Positioning System (GPS) is another method that is often used to monitor landslide movements (Bonnard et al. 1996; Wasowski et al. 2004; Mills et al. 2005; Webster and Dias 2006; Yin et al. 2008; Zhang et al. 2008). Precision of measurements is in the range of cm to mm. However, the applicability of this method depends on the visibility of satellites which may not be the case in narrow valleys, densely forested areas or on steep cliffs.

The methods described above are applicable to measure and monitor ground deformation at the surface. In order to understand landslide behaviour subsurface measurements are necessary. Basic approaches are pits and trenches which can be used to investigate e.g., the depth of a landslide and the position of shear surfaces or to take undisturbed material samples. Generally, pits and trenches can only be established on shallow movements. Examples are given by Bromhead et al. (2000), Clark et al. (2000) and Topal and Akin (2008). Penetration tests can also be performed to investigate stiffness of subsurface materials. More often, drillings are utilised to investigate landslide bodies. An ample variety of drilling devices is available on the market from simple handheld sounding poles to truck-sized rotary drilling machines. Besides the advantage of directly probing the landslide body and having the opportunity to take core samples, sensors can be applied within the boreholes to further investigate subsurface movement and hydrological processes.

In many cases inclinometers are used to determine subsurface movement of landslides (Borgatti et al. 2006; Bonnard et al. 2008; Bressani et al. 2008; Jongmans et al. 2008; Mihalinec and Ortolan 2008; Yin et al. 2008). General remarks on the use of inclinometers for landslides research are provided by Stark and Choi (2008). Inclinometers consist of a flexible drilled pipe which is placed vertically into a drilled borehole. A high-precision probe is inserted and the inclination of the pipe is measured in even distances, for example, every e.g., 50 cm. Repeated measurements give information of the occurred inclination changes in downslope and horizontal direction for the entire length of the pipe. However, it is important that inclinometers are fixed into the stable ground beneath the shear surface to prevent data bias. Automated inclinometer s are commercially available and usually consist of several inclinometer probes connected to each other to a chain, or automatic systems where the probe automatically moves within the pipe. Within landslide monitoring the use of automatic inclinometer and inclinometer chains has been described by for example, Lollino et al. (2002) and Olalla (2004), Volkmann and Schubert (2005) and Wienhöfer and Lindenmaier (2009). However, inclinometers can only withstand a certain amount of displacement before pipes break. This makes them especially applicable for monitoring of slow moving landslides, but also for detection of shear processes in faster moving landslides.

A more recent method for the detection of subsurface movements and deformation is Time Domain Reflectometry (TDR). Barendse and Machan (2009) note that inclinometers can determine the magnitude and direction of ground deformation, while TDR is primarily used to identify depths of active shearing. The TDR method has initially been developed in the 1950s for locating discontinuities in power transmission cables (Pasuto et al. 2000). TDR has first been used within landslide research in the 1980s in underground coal mine monitoring (Olalla 2004) and since then applied to several other case studies (Pasuto et al. 2000; Barendse and Machan 2009; Singer et al. 2009; Yin et al. 2010a). The principle of TDR is based on an electric signal sent through a coaxial cable. Shear movements deform the cable which creates a spike in cable signature and depth can be detected from the signal. Laboratory tests of TDR method for detection of shear processes have been performed by Baek et al. (2004) and Blackburn and Dowding (2004). Pasuto et al. (2000) compared TDR cables to inclinometer measurements and extensometers. Their result was that TDR cables are less sensitive to deformations but can withstand a larger displacement than usual inclinometers. The higher stability of

TDR cables make them a good choice for monitoring faster moving processes like the Gschliefgraben flowslide in Austria (Marschallinger et al. 2009).

Wire or rod extensometers are used to monitor the distance between two points and are frequently utilised in surface movement investigations (Furuya et al. 2000; Angerer et al. 2004; Barla et al. 2004; Willenberg et al. 2004; Wu et al. 2008). Extensometers are in most cases applied to investigate surface movements but can also be installed within boreholes (Bloyet et al. 1989; Krauter et al. 2007). Accuracy of extensometers depends on the length measured and usually is in the sub-mm range.

Tiltmeters are able to give high resolution information on inclination and have been applied to several landslide monitoring systems (Clark et al. 1996; Meidal and Moore 1996; Barton and McCosker 2000; Blikra 2008; García et al. 2010).

Crackmeters are used to monitor displacements in the sub-mm range at joints and cracks in rocks, buildings and other structures. The application of crackmeters has been described by several authors (e.g., Keaton and DeGraff 1996; Greif et al. 2004; Olalla 2004; Vlcko 2004; Moore et al. 2010).

The mentioned field based methods only give information on ground displacements for points or along lines. However, spatial methods are also available that give information on displacement for entire slopes.

In recent years many studies utilised Terrestrial Laser Scanning (TLS) for monitoring of geomorphological processes. The technique is similar to LiDAR, but ground-based. In contrast to LiDAR it is appropriate for steep cliffs and rock faces as the scanner can be placed in front of it. TLS scans are used to create three dimensional DTM which can further be analysed quantitatively within GIS or CAD environments to assess e.g., the volume of displaced material between measurements. Precision of TLS is heavily dependent on distance to the target and ranges from centimetres to mm, as well as environmental conditions such as rain or vegetation. General remarks on TLS and its usage for monitoring geomorphological processes are provided by Prokop and Panholzer (2009) and Schaefer and Inkpen (2010). Many case studies applied TLS for landslide monitoring (e.g., Mikoš et al. 2005; Rosser et al. 2005; Rosser and Petley 2008; Avian et al. 2009; Baldo et al. 2009; Oppikofer et al. 2009; Abellán et al. 2010).

SAR methods can also be applied in ground-based studies, which are frequently termed Slope Stability Radar (SSR) (Van Westen 2007). The major advantages of this method are that they provide high precision data in sub-millimetre range without being affected by weather conditions and without the need to install reflectors or ground marks. However, vegetation drastically decreases accuracy. Luzi et al. (2005) used a ground-based DinSAR system to monitor displacement on the Italian Tessina landslide and compared the measurements to regular theodolite surveys. Based on comparable displacement results by both methods they conclude that InSAR is also applicable for landslide early warning systems. Several other research projects installed SSR systems to monitor displacements of landslides (Canuti et al. 2002; Antonello et al. 2004; Casagali et al. 2004; Eberhardt et al. 2008; Bozzano et al. 2010; Casagli et al. 2010).

Another method that has increasingly been used in recent years is Brillouin Optical Time-Domain Reflectometry (BOTDR). These optical fibres can be used for measurement of ground deformations along profiles. The principle of this method is based on an interaction of pulsed beam and photons that are thermally excited within the light propagation medium (Wang et al. 2008a), which are affected by temperature and strains. Laboratory simulations to test the applicability of BOTDR (Dai et al. 2008; Wang et al. 2008a), as well as field applications (Higuchi et al. 2007; Dai et al. 2008; Shi et al. 2008a, b; Moore et al. 2010) have been described.

2.2.3 Hydrological Measurements

Given the great importance of rainfall and slope hydrology for landslide triggering, these factors are frequently analysed and monitored within landslide research. Climatic factors such as rain, snowfall, temperature and wind are usually measured at climate stations, which are commercially available or in many cases provided by meteorological agencies. Measurement of ground-water conditions such as pore pressures and soil water suction is usually accomplished by using piezometers and tensiometers. An overview on different types of these sensors can be found in Kneale (1987). Piezometers are probably the most common hydrological sensor utilised for landslide research (e.g., Wu et al. 2008; Yin et al. 2008; Calvello et al. 2008; Ching-Chuan et al. 2009; Yin et al. 2010a) and come as simple standpipe or more advanced vibrating wire piezometers. Piezometers measure the pressure of water in saturated soils and therefore give information on the height of the groundwater table within a soil. Tensiometers measure matrix potentials and are frequently utilised to assess the soil suction in the vadose zone (Li et al. 2004; Rinaldi et al. 2004; Montrasio and Valentino 2007; Greco et al. 2010). Piezometers and tensiometers are usually installed within boreholes or directly into the soil at trenches.

In recent years Time Domain Reflectometry (TDR) has also been applied to measure volumetric soil water contents. Greco et al. (2010) compared TDR sensors with tensiometers and concluded that TDR might be more useful for landslide monitoring and early warning since TDR measurements of soil water content change smoothly, while soil suction showed abrupt steep fronts. More examples of TDR application for assessing soil water are presented by e.g., Hennrich (2000), Tohari et al. (2004) and Kim (2008).

The chemical properties of ground and pore water have a widely acknowledged effect on shear strength and affect slope stability (Di Maio and Onorati 2000; Angeli et al. 2004) by for example, influencing the mechanical behaviour of clays (Leroueil 2004). However, monitoring of ground water composition is only rarely included in landslide monitoring systems (Sakai and Tarumi 2000; Montety et al. 2007; Sakai 2008).

2.2.4 Geophysical Measurements

Several methods from geophysics have been utilised for landslide research, mainly for prospection of landslide bodies and for investigation of hydrological processes acting within landslides. However, wider application of geophysics in landslide research have been hindered for two reasons (Jongmans and Garambois 2007): geophysical methods provide images of geophysical parameters which are not directly linked to geological parameters required by geotechnical engineers and geomorphologists; and the overestimation of the quality and reliability of results among some geophysicists. The main advantages of geophysical methods compared to standard geotechnical approaches are that they are non-invasive and can be applied to large areas for a low cost. However, the main disadvantages are the decrease of resolution with depth, the non-uniqueness of solutions for data inversion and interpretation, and the in-direct information (Jongmans and Garambois 2007). Generally, geophysical methods are used for prospection of landslide bodies, detection of discontinuities and shear surfaces, as well as for investigation of hydrological regimes. Measurements are usually short-term and only a few long-term monitoring exist (Supper and Römer 2003; Lebourg et al. 2005). Geophysical methods will only briefly be presented here, more detailed reviews on geophysical application are provided by many introductive textbooks (Telford et al. 1990; McGuffey et al. 1996; Parasnis 1997; Reynolds 1997; Kearey et al. 2002; Milsom 2003; Schrott et al. 2003; Knödel et al. 2005).

Seismic methods are based on the velocity measurements of seismic waves in subsurface materials. Generally, denser material causes faster wave propagation. At layer interfaces waves are partly reflected, but also partly transferred into depth due to refraction. In geomorphological applications seismic signal is usually induced by a sledge hammer that is pounded on a steel plate. Penetration depths of more than 30 m can be reached by more powerful sources e.g., drop weights or explosives) (Schrott and Sass 2008). Measurements are taken by geophones which are located at even distances along a profile. A number of different seismic techniques have been established, of which seismic reflection, seismic refraction and seismic tomography are the most common. Although seismic methods proved to be suitable for many geomorphological studies which require definition of subsurface properties (Hecht 2001), such as determination of active layer in permafrost or volumes of sediment bodies, problems may occur if low velocity layers are sandwiched in high velocity layers (Schrott and Sass 2008). Examples of dedicated landslide subsurface characterisation applying seismic methods are provided by several authors (Schmutz et al. 2000; Willenberg et al. 2002; Meric et al. 2004; Meric et al. 2005; Heincke et al. 2006, 2010).

A variation of seismic method is applied to record fracture signals produced by deformation within landslides, and to locate fracture both in space and time. These methods can be distinguished as micro-seismic, nano-seismic and passive seismic (Joswig 2008). Instead of creating a seismic signal by e.g., a sledge hammer, these methods use the acoustic signals emitted by deformation processes by “listening” to ruptures. This method yields information on depth and mode of slope deformation (Bláha 1996). An increasing number of studies employ such approaches in laboratory tests (Dixon and Spriggs 2007; Ishida et al. 2010) and field applications (Merrien-Soukatchoff et al. 2005; Amitrano et al. 2007; Meric et al. 2007; Häge and Joswig 2009; Walter and Joswig 2009).

Ground penetrating radar (GPR) has increasingly been used in recent years in many geomorphological research projects to investigate subsurface (Sass and Krautblatter 2007; Gomez et al. 2009). Advantages of the method include high resolution and wide range of penetration depth (Jongmans and Garambois 2007). In landslide research, GPR is generally used to determine landslide boundaries and discontinuities, such as shear surfaces and cracks in rock, but GPR is also sensitive to groundwater. High-frequency electromagnetic waves are emitted by an antenna and wave propagation is determined by dielectric properties of the subsurface materials (Schrott and Sass 2008). Emitted pulses are reflected by inhomogeneities and received by a second antenna. The antennas are usually moved along a profile, and travel times of pulses are measured and subsequently inverted into 2D images. Penetration depth depends on material properties and frequencies used, but can be up to 60 m if conditions are favourable (Schrott and Sass 2008). Landslide related research applying GPR are provided by (Bichler et al. 2004; Avila-Olivera and Garduño-Monroy 2008; Sass et al. 2008; Willenberg et al. 2008; Pueyo-Anchuela et al. 2009). However, GPR is generally only applied for short-term measurement campaigns, and has not been employed in monitoring projects. Still, Roch et al. (2006) propose repeated GPR monitoring for rockfall monitoring.

Electrical resistivity and spontaneous potential are both geoelectrical methods. Self-potential measurements investigate natural electrical potential by assessing potential differences between pairs of electrodes. If electrochemical processes are absent within a slope changes reflect changes of fluid flows, i.e. ground water. Spontaneous potential measure can more easily be deployed and monitored compared to the resistivity method (Jongmans and Garambois 2007); however, electrical resistivity measurements are more common (Telford et al. 1990). This method is based on the measurement of electrical potentials between an electrode pair while a direct current is transmitted by another electrode pair (Schrott and Sass 2008). Several different procedures and array setups exist for electrical resistivity measurements which have to be chosen depending on the research question, study site properties and desired penetration depth. Electrical resistivity is affected by the nature of material, in particular clay content, water content, as well as rock weathering and fracturing (Jongmans and Garambois 2007). Geoelectric geophysical methods have frequently been used for landslide prospection and determination of internal structure, such as the location of shear surfaces and boundaries of landslide bodies (Jomard et al. 2007; Deparis et al. 2008; Sass et al. 2008; Heincke et al. 2010). However, sensitivity of resistivity to water content also allows detection of groundwater tables or preferential flow (Hiura et al. 2000; Kusumi et al. 2000; Lebourg et al. 2005). Geoelectrical methods are usually applied for short-term measurement campaigns, and only a few case studies describe continuous monitoring (Supper and Römer 2003; Lebourg et al. 2004).

2.3 Landslide Modelling

Landslide modelling is, along with experimental subsoil exploration and experience driven safety assessment, one of the main tasks of slope stability practice (Janbu 1996). Models are applied to analyse current stability status and to predict slope behaviour under certain conditions such as rainfall events or scenarios for environmental change. Moreover, models are used for the back-analyses of already failed slopes and for assessment of effectiveness of geotechnical stabilisation measures (Barla et al. 2004). However, when dealing with modelling it is important to keep in mind, that all models are necessarily simplified generalisation and approximations of processes which are occurring in nature (Favis-Mortlock and De Boer 2003).

Modelling of landslide failures can be either qualitative or quantitative (Carrara et al. 1999). Qualitative approaches integrate descriptive prediction and the opinion of experts, while quantitative applications are based on numerical simulations. Landslide modelling approaches can broadly be separated into models that are focussing on single landslide processes (i.e. local models), and models with greater spatial extent (i.e. regional models) (Crozier and Glade 2005).

Local approaches to landslides have a long tradition within geotechnical engineering slope stability practice, while regional applications have increasingly emerged since the wide availability of powerful computers and GIS. A brief summary on regional and local approaches to model landslides in order to predict slope failures is given in the following sub-chapters.

2.3.1 Regional Models

Regional landslide modelling methods generally focus on either landslide susceptibility or hazard, or eventually landslide risk. Landslide susceptibility is defined as the "*probability of spatial occurrence of slope failures, given a set of geo-environmental conditions*" (Guzzetti et al. 2005, p. 113). Therefore landslide susceptibility modelling seeks to delineate the terrains' potential for landslide processes. In contrast, landslide hazard is defined as "*the probability of occurrence within a specified period of time and within a given area of potentially damaging phenomenon*" (Varnes 1984). The term hazard therefore also requires definition of magnitude of potential events, that is, affected area, volume and velocity of expected landslide events (Reichenbach et al. 2005). The term landslide risk refers to the outcomes of landslide events and is defined as "*the expected degree of loss due to a landslides and the expected number of lives lost, people injured, damage to property and disruption of economic activity*" (Varnes 1984). While landslide susceptibility and hazard concentrate on the causes and properties of landslides, risk also refers to the consequences and outcomes of such processes, which are strongly dependant on the vulnerability of the effected people and infrastructure.

Soeters and Van Westen (1996) distinguish between four distinct approaches for regional landslide hazard analysis, i.e. inventory-based, heuristic, statistic and deterministic approaches.

Landslide inventories allow for detailed analyses of landslide distribution and in case of multi-temporal inventories activity patterns and form the basis for regional modelling of landslide susceptibility, hazard and risk.

Heuristic methods integrate the knowledge and experience of geomorphological and geotechnical experts to derive a regional map of landslide susceptibility and hazard. Soeters and Van Westen (1996) distinguish between geomorphological analysis (Kienholz et al. 1984; Cardinali et al. 2002; Reichenbach et al. 2005) and weighted combination of thematic maps (Pachauri et al. 1998; Nagarajan et al. 2000; Dikau and Glade 2003; Moreiras 2005; Petley et al. 2005a).

Statistical methods are the most frequently applied method to model regional landslide susceptibility and hazard, and to predict future slope failures (Armbruster 2002). Herein, a statistical relationship between possible landslide causative factors and the presence of existing landslides is established, and used for prediction of future landslide by spatial interpolation. A vast range of different methods has been developed. Bell (2007) provides a extensive list of statistical methods, of which the most frequently applied are bivariate regression (Ayalew et al. 2004; Süzen and Doyuran 2004), multiple regression (Carrara 1983; Chung et al. 1995), discriminant analyses (Ardizzone et al. 2002; Carrara et al. 2003; Guzzetti et al. 2006), logistic regression (Atkinson et al. 1998; Ohlmacher and Davis 2003; Süzen and Doyuran 2004; Brenning 2005), neural networks (Fernández-Steeger et al. 2002; Lee et al. 2003; Catani et al. 2005), support vector (Brenning 2005), bayesian statistic (Chung and Fabbri 1999; Lee et al. 2002; Neuhäuser 2005), fuzzy logic (Tangestani 2003; Dewitte et al. 2006; Lee 2006) and likelihood ratio (Chung et al. 1995; Chung 2006; Demoulin and Chung 2007).

Regional deterministic models apply physically-based simulations to assess landslide susceptibility expressed chiefly as FoS, and provide useful insights into landslide causes (Carrara et al. 1992). The most frequently applied methodology for regional deterministic modelling is based on distributed hydrological modelling and stability calculation using a simplified approach, i.e. the infinite-slope model. Hydrological modelling is essentially based on topographical flow routing and the simulated development of soil saturation above an impermeable layer (O'Callaghan and Mark 1984; Fairfield and Leymarie 1991; Freeman 1991; Quinn et al. 1991; Lea 1992; Costa-Cabral and Burges 1994; Terlien et al. 1995; Tarboton 1997). Calculation of slope stability utilises geotechnical parameters such as cohesion and internal friction, which can be measured in the field or laboratory (Soeters and Van Westen 1996; van Westen et al. 1997). The infinite-slope model estimates stability for single grid-cells of a DTM and neglects any effects of neighbouring areas. Moreover, deterministic methods are only applicable when geomorphic and geologic conditions are fairly homogenous over the entire study area and landslide types are simple (Soeters and Van Westen 1996). Due to these limitations, regional deterministic models are only suitable for simple landslide processes, such as shallow translational landslides. The most widely used models for regional deterministic analyses are

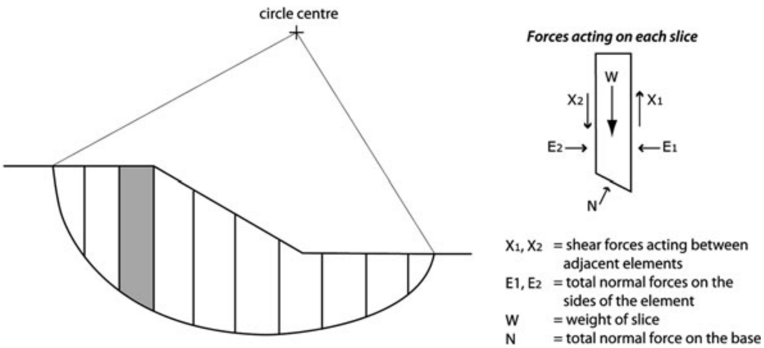

Fig. 2.6 Simplified illustration of method of slices (after Conolly 1997)

TOPMODEL (Montgomery and Dietrich 1994; Casadei et al. 2003; Meisina and Scarabelli 2007), SHALSTAB (Dietrich et al. 1998; Morrissey et al. 2001; Huang Jr et al. 2006), and SINMAP (Pack et al. 1998, 2001, 2005; Zaitchik and van Es 2003; Pack and Tarboton 2004; Kreja and Terhorst 2005; Thiebes 2006; Deb and El-Kadi 2009), but similar studies have also been performed by other authors (Hammond et al. 1992; Terlien et al. 1995; Wu and Sidle 1995; van Westen et al. 1997; Wu and Sidle 1997; Sidle and Wu 1999; Xie et al. 2004; Claessens et al. 2005).

2.3.2 Local Models

Models for the analysis of single slope failures, i.e. local models, have a long tradition in geotechnical slope stability practice. These models have frequently been applied to assess the stability of human-made or natural slopes, and the design of slopes, such as embankments, road cuts, open-pit mines etc. Moreover, physically-based models for single slopes allow detailed investigation of failure processes, assessment effects of triggering events, and assessment of the effectiveness of remedial measures and stabilisation works.

Today, a wide range of computer calculation programs are available for numerical slope stability assessment. Despite the development of more sophisticated numerical models, limit-equilibrium methodology is still widely applied (Abramson 2002). In the following a short overview of local landslide modelling methods and techniques is presented. It is beyond the scope to review the theoretical background and mathematical and mechanical derivation of local stability calculation. These can be found in the literature sources provided or in various textbooks (Chandler 1991; Bromhead 1998; Abramson 2002; Aysen 2002; Eberhardt 2003a; Ortigão and Sayao 2004; Duncan and Wright 2005; Gitirana Jr 2005; Cheng and Lau 2008).

Limit-equilibrium methods provide a mathematical procedure to determine the forces within a slope that drive and resist movement. The factors included in the calculation have been presented in Sect. 2.1.2. Limit-equilibrium analysis usually calculates stability for discrete two-dimensional slices of a slope and for assumed or known potential shear surfaces (Fig. 2.6), but three-dimensional approaches have also been developed. Shear strength of materials along shear surface is assumed to be governed by linear or nonlinear relationship between shear strength and normal stress (US Army Corps of Engineers 2003). The result of limit-equilibrium analysis is a global FoS for shear surface, which provides a snapshot on stresses and resisting forces relationship.

Several numerical methods are available today which assist in locating critical shear surfaces, this is, where the lowest FoS is prevalent. The most widely applied methods are Bishop's simplified approach, which accounts for circular slip surfaces, and Janbu's method for con-circular, i.e. polygonal shear surfaces. Other methods like the infinite-slope wedge method, ordinary slice method, general slice method, Spencer's method, Morgenstern and Price's method, and some others are reviewed elsewhere (Graham 1984; Anderson and Richards 1987; Nash 1987). Given the wide use of numerical limit-equilibrium methods for slope stability analysis in geotechnical practice, most available models allow assessment of effects of e.g., external loads or remedial stabilisation structures, such as soil nails or other reinforcements.

However, limit-equilibrium methods also comprise some drawbacks. The resulting FoS represents a global value for a two-dimensional slope profile, where movement occurs if the FoS < 1.0. However, (Bonnard 2008, p. 46) notes that limit-equilibrium methods only provide an approximation of force balance within landslides and that in reality displacements may occur with a FoS between 1.0 and 1.1–1.15. Moreover, the FoS is an average value for an assumed critical failure surface and provides no information about the actual distributions of stresses or the progressive development of unstable state (Eberhardt et al. 2004).

A second family of stability models on a local scale is concerned with continuum modelling. The entire slope mass is divided into a finite number of elements and represented as a mesh. Continuum approaches include finite-difference and finite-element methods. Finite-difference methods provide numerical approximations of differential equations of equilibrium, strain–displacement relations or the stress–strain equations (Eberhardt 2003a). In contrast, finite-element procedures exploit approximations to the connectivity of elements, and continuity of displacements and stresses between elements (Eberhardt 2003a). However, in both methods the problem domain is discretised into a set of subdomains or elements. In contrast to limit-equilibrium analysis, continuum modelling software allows for complex time-dependant landslide analysis by including constitutive models such as elasticity, elasto-plasticity and strain softening.

A third family of local landslides models are discontinuum methods, where slopes are represented by distinct blocks which dynamically interact during movement or deformation. The underlying concept of these methods is that limit-equilibrium is repeatedly computed for each block, so that complex non-linear interaction can be accounted for (Eberhardt 2003a).

Three variations of discrete-element variation can be distinguished. Distinct-element methods are based on a force–displacement law to describe interaction between deformable elements, and a law of motion to numerically simulate displacements. Discrete element methods are computationally intensive as many case studies involve a very high number of interacting discrete objects. More detailed information is provided by (Hart 1993) and (Jing 1998). Discontinuous deformation analysis simulates interaction of independent blocks along discontinuities, such as fractures and joints. In contrast to distinct-elements methods, discontinuous deformation analysis accounts for displacement instead of simulating forces (Cundall and Strack 1979). Particle flow methods represent slopes with spherical particles that interact through frictional sliding contacts (Eberhardt 2003a).

Below, an overview of commercially available local landslide analysis and simulation models is presented. This is, however, only a selection of models frequently applied in landslide research as a complete summary is far beyond the scope of this study.

GGU is a CAD-based (Computer Aided Design) stability model which allows for predicting stability based on Bishop's and Janbu's, as well as general wedge and vertical slice method. Moreover, stabilising factors such as anchors, soil nails and geosynthetics can be included in the modelling process. However, the GGU stability software does not account for dynamic hydrological modelling. Several applications utilising the GGU stability software are available (Chok et al. 2004; Schneider-Muntau and Zangerl 2005; Kupka et al. 2009; Hu et al. 2010).

Galena is another numerical software solution available which includes limit-equilibrium analysis. It includes Bishop's and Spencer-Wright method and Sarma method, which utilises non-vertical slices for slope stability analysis. However, the Galena software was developed mainly for slope design in open-pit mines, and only few project applied it to analyse landslides (Kumar and Sanoujam 2006).

The program Xslope is capable of calculating slope stability based on Bishop's or Morgenstern and Price's method, and is available through University of Sydney. It does not include hydrological modelling, but pore water pressure from an external finite element steady-state seepage model can be integrated. Several case studies are available that describe the application of Xslope (Lee et al. 2001; Hubble 2004; Cássia de Brito Galvão et al. 2007).

Another model for limit-equilibrium analysis of soil and rock slopes is provided by SLOPE/W which includes several methods (Morgenstern-Price, Spencer, Bishop, Ordinary, Janbu and more). Also, several soil strength models are available. Stability analysis may be performed using deterministic or probabilistic input parameters. However, dynamic hydrological modelling of pore pressures is not included in SLOPE/W, but can be imported from SEEP/W, a finite-element software by the same company. Moreover, external stresses by earthquakes for example, and also the effects of reinforcements can be analysed. The use of SLOPE/W, also in combination with SEEP/W is fairly widely acknowledged in recent landslide research (Anderson et al. 2000; Rahardjo et al. 2007; Cascini et al. 2008; Heng 2008; Yagoda-Biran et al. 2010; Rahimi et al. 2010; Navarro et al. 2010).

SVSlope is a slope stability software with a similar complexity and range of available methods as SLOPE/W. However, three-dimensional limit-equilibrium analyses can also be performed for which slopes are represented as columns to analyse stability by a series of two-dimensional calculations. Moreover, a finite-element stability analysis tools have been added to compute stresses and strains.

Several authors presented case studies applying SVSlope (Gitirana Jr 2005; Fredlund 2007; Gitirana Jr. et al. 2008).

A similar program is Clara-W, which performs two and three-dimensional stability limit-equilibrium analysis (Eberhardt 2003b; Stead et al. 2006; Cotza 2009; Montgomery et al. 2009).

CHASM (Combined Hydrology And Stability Model) is a coupled hydrology and slope stability model for limit-equilibrium analysis. The software program integrates simulation of saturated and unsaturated hydrological processes to calculate pore water pressures, which are then incorporated into stability computation. CHASM is essentially two-dimensional but hydrological simulations can be extended to account for flow concentration at topographic hollows. Moreover, vegetation and stabilisation measures can be integrated into Janbu and Bishop stability simulations. Furthermore, a simple empirical-based run-out simulation is integrated into the model. CHASM was also employed within this study and a more detailed review on CHASM methodology is presented in Sect. 5.1.3.2.

The CHASM model has been applied by several research projects, for example in New Zealand (Wilkinson et al. 2000), Malaysia (Collison and Anderson 1996; Lateh et al. 2008), Hong Kong (Wilkinson et al. 2002b), the Caribbean (Anderson et al. 2008), Kuala Lumpur (Wilkinson et al. 2000; Wilkinson et al. 2002a), and Greece (Matziaris et al. 2005; Ferentinou et al. 2006; Sakellariou et al. 2006). Common applications of CHASM include investigations of effects of rainfall on slope hydrology and subsequently on slope stability (Matziaris et al. 2005; Ferentinou et al. 2006). Other studies compared CHASM to other slope stability model and carried out sensitivity analyses for rainfall, groundwater conditions and slope geometry (Lloyd et al. 2004).

Sensitivity analysis of CHASM has been carried out for geotechnical and hydrological parameters (Hamm et al. 2006), hydraulic conductivity (Ibraim and Anderson 2003), vegetation (Wilkinson et al. 2002b) and slope stability methods (Wilkinson et al. 2000). Comparisons of field measurements of pore water pressures with modelled results are provided by Anderson and Thallapally (1996) and Hennrich (2000). Other applications of CHASM include studies to improve criteria for geotechnical slope design (Anderson et al. 1996), and validation of rainfall thresholds to enhance the performance of a landslide early warning system in Kuala Lumpur (Lloyd et al. 2001). Later works of Wilkinson et al. (2002a) implemented a slope information system in which pre-defined slopes can be modelled in CHASM using a variety of input parameter constellations. Recent applications of CHASM include the work of Karnawati et al. (2005) in which the aim was to provide guidance to local population in Java, Indonesia on how to judge stability and hazardousness of slopes. Back analysis of recent landslides within CHASM was applied by Anderson et al. (2008) in the Caribbean. Based on modelling results critical hydrological situations were determined and an effective slope drainage system was designed.

Several models are available from RocScience for calculation of stability, stresses and displacement for rock and soil. Phase[2] offers two-dimensional elasto-plastic finite-element stress analysis for underground or surface excavations with integrated groundwater seepage modelling (Hammah et al. 2008, 2009). The program Slide utilises two-dimensional limit-equilibrium analysis with built-in finite-element hydrological modelling. Generally, capabilities of Slide are similar to other limit-equilibrium programs described above. Case studies utilising Slide are described by several authors (Kjelland et al. 2004; Hadjigeorgiou et al. 2006; Hammah et al. 2006; Brandon et al. 2008; Topal and Akin 2008).

Plaxis is a collection of finite-element methods for numerical analysis of deformation and stability in geotechnical engineering in two and three dimensions. Moreover, unsaturated groundwater flow and pore pressures, as well as their effects on slope stability can be simulated. Static loads and dynamic loads and stability in response to earthquakes, as well as non-linear, time-dependent and anisotropic behaviour of soils and/or rock are more features of this complex software. Plaxis-aided research concerned with landslides has been provided by several authors (e.g., Spickermann et al. 2003; Ausilio et al. 2004; Comegna et al. 2004; Kellezi et al. 2005; Keersmaekers et al. 2008; Majidi and Choobbasti 2008; Chang et al. 2010).

FLAC (Fast Lagrangian Analysis of Continua) is a two-dimensional explicit finite difference program widely acknowledged in analysis of plastic deformation (Cala et al. 2004; Maffei et al. 2004; Chugh and Stark 2005; Petley et al. 2005d; Jian et al. 2009). Slopes are represented by elements which form a grid and behave according to a prescribed linear or nonlinear stress and strain law. Deformation of the grid allows for flowing and plastic-deformation, and large strain can be simulated. A simplified of this model is FLAC/Slope, which is sold by the same company. Moreover, a three-dimensional version, FLAC3D, is available and has frequently been applied within research (Teoman et al. 2004; Pasculli and Sciarra 2006; Sitharam et al. 2007; Poisel et al. 2009).

DAN, and its related version DAN-W and DAN3D, are software tools used for dynamic run-out analysis of rapid landslides processes such as rock avalanches (Hungr 1995). The core of the models is a Lagrangian solution of the integrated equations of motion which is implemented for thin elements of the flowing mass. The model simulates travel distance, velocity and flow depth and volumes in iterative time-steps. Many case studies acknowledge the use of DAN codes (Hungr 1995; Sosio et al. 2008; Hungr and McDougall 2009; Pirulli 2009).

UDEC (Universal Distinct Element Code) simulates the response of discontinuous media such as jointed rock which subject to loading. The two-dimensional analysis allows for rigid or deformable blocks. However, the related 3DEC model offers similar modelling capabilities but in three dimensions. Several case studies applied UDEC on rock slopes (Bandis et al. 2000; Bozzano et al. 2000; Chen et al. 2000; Gunzberger et al. 2004; Watson et al. 2004; Gong et al. 2005; Zhao et al.

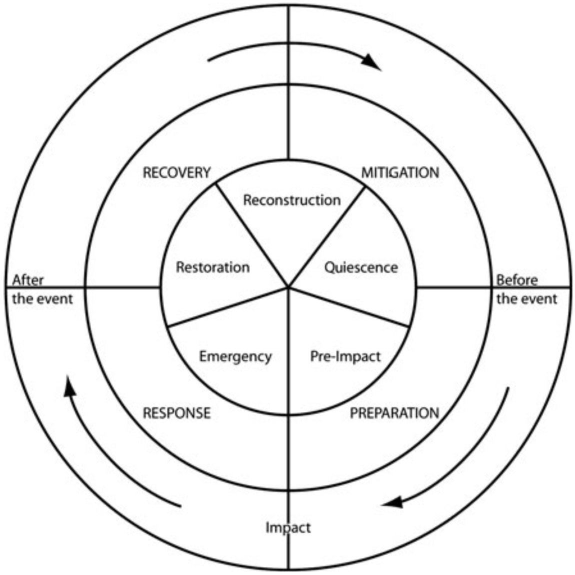

Fig. 2.7 General risk management cycle (after Alexander 2000, 2002)

2008), and 3DEC (Cheng et al. 2006; Ming-Gao et al. 2006; Lato et al. 2007; Bai et al. 2008).

2.4 Landslide Early Warning Systems

In the following an introduction to early warning and the challenges of early warning systems is presented. Therein, general aspects on social and technical aspects of early warning are demonstrated. The focus, however, is put on landslide early warning. More information regarding early warning systems for natural hazards in general is provided by several other authors (e.g., Zschau et al. 2001; Zschau and Küppers 2003; Dikau and Weichselgärtner 2005; Hall 2007; Schuster and Highland 2007; Felgentreff and Glade 2007; Glantz 2009). In addition, a review of existing landslide early warning systems worldwide is presented. It is beyond the scope to give a complete summary of all existent systems, but to illustrate a wide range of technical applications and to highlight integration of social components into early warning process.

Early warning can broadly be defined as the timely advice before a potentially hazardous phenomenon occurs. Dikau and Weichselgärtner (2005) add that the effective use of information for early warning is an important element of general risk management which includes activities such as hazard zoning and prediction, warning communication, disaster prevention and evacuation planning (Fig. 2.7). Good early warning systems therefore comprise identification and estimation of hazardous processes, communication of warnings and adapted reaction of local population. Moreover, early warning systems have to be embedded into local communities to ensure effectiveness of the entire system.

A more pin-pointed definition is used by UNISDR (2009) where early warning system are described as "*the set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss*".

Early warning systems have been developed for a wide range of natural hazards of which extreme weather events, floods and tsunamis are maybe the best known. However, also for processes such as volcanic eruptions, droughts, snow avalanches, earthquakes and landslides early warning systems have been installed. Extensive information on applied early warning systems is presented by several publications in the United Nations International Strategy for Disaster Reduction (UNISDR 2004a, b, 2006a, b). However, specialized landslide early warning systems are not described therein.

Within the UNISDR a Platform for the Promotion of Early Warning Systems (UNISDR-PPEW) has been founded to stimulate the advance of early warning. UNISDR puts an emphasis on social aspects of early warning and promotes the development of people-centred early warning systems (UNISDR 2006b). Four essential key parts for effective early warning can be defined (UNISDR 2006b):

1. Knowledge about the risks that threaten a community
2. Monitoring and warning service for these risks
3. Dissemination and communication of warning messages in a way that is understood by the local population
4. Response capability of involved people, who need to know how to react appropriately in case of a warning.

These four segments are also reflected in a general distinction of early warning proposed by Zschau et al. (2001), who distinguish the elements of prediction, warning and reaction. These components constitute the early warning chain. The segments of this chain have to be tightly connected and interlinked in order to provide an effective measure for risk reduction.

Prediction is strongly influenced by a natural science and technological perspective and aims to improve knowledge on the hazardous process itself and its timing, size, extent, severity, duration etc. The time-span between warning and the occurrence of the hazardous event is another important issue of prediction, and can last from seconds (for e.g. earthquakes) to months (for e.g., droughts) (Zschau et al. 2001).

The second element, warning, can be regarded as the critical element within the early warning chain (Dikau and Weichselgärtner 2005). Prediction has to be transferred into an adequate warning message and distributed to the target population. Several communication channels (e.g., SMS, Fax, Email, sirens) can be used to distribute warning messages. However, effective warning is not only a technical problem, but is also dependant on the social and political decisions and the legal framework (Zschau et al. 2001). Moreover, it is important that communication of warning is carefully planned (Mayer and Pohl 2010). According to Kunz-Plapp (2007) warning messages should be believable, clearly formulated, adapted to the context of the target group, and should contain clear instructions on appropriate protection action.

Reaction is the third component of early warning, in which warning messages should lead to appropriate action such as evacuation of hazardous areas. Decision makers have to initiate protection actions based on the warning message. Effective reaction to warning messages primarily depends on the administrative and organisational circumstances (Zschau et al. 2001).

Given the complex conditions of early warning it is obvious that purely technical approaches cannot provide effective early warning. It has already been noted by the fathers of hazard research that it is important to know how technological advances in early warning systems can be used to more efficiently trigger appropriate reactions of populations to prevent losses from natural hazards (White and Haas 1975). Still, for a long time advances in early warning systems were primarily related to the use of more sophisticated monitoring equipment while social aspects of early warning were neglected (Zschau et al. 2001). This is problematic, as many communities cannot afford expensive high-tech warning systems. Sorensen (2000, p. 214) states that "*better local management and decision making about the warning process are more critical than promoting more advanced technologies*, *although both would help*". Many important social aspects are not accounted for in technical approaches to early warning. However, the importance of the hazard awareness can be illustrated by recent disaster events, such as devastating the tsunami in the Indian Ocean in 2004 which caused more than 200,000 fatalities. Even though no early warning system was installed, this disaster illustrates a major problem in early warning. As many people did not know that a sudden decrease in sea-level precedes the occurrence of a tsunami, no appropriate reaction could be initialised. If a threatened population is not informed about potential hazards, their consequences and suitable protective actions, early warning cannot be effective.

Although an early warning system could have enabled many people to evacuate coastal areas, early warning systems cannot provide full security from hazardous events. An example of this took place in April 2010, when a train derailed in the Etsch Valley, South Tyrol, Italy, because of a rockfall occurring above the track. Even though an automatic early warning system existed to close the track in case of blockages, it failed in this event because the rockfall took place right above the passing train (Murmelter 2010).

Moreover, it is important to keep in mind that only people and moveable objects can benefit from early warnings and not stationary objects such as infrastructure. An alarm can motivate people to escape from potentially dangerous situations, but it does not stop the hazardous event itself (Hübl 2000). Therefore, early warning systems do not substantially decrease property damage (National Research Council 2004).

Although early warning systems can be an effective tool for risk reduction (Dikau and Weichselgärtner 2005) they can also increase the risk. Increased risk may be due to a false sense of security and building of higher value infrastructure in potentially hazardous areas.

Uncertainties always prevail in hazard prediction and are also a major challenge for early warning (UNISDR 2004b). Storms may change their track, or lose their strength over time, earthquakes may be expected for a large area, but no exact location can be determined. For many hazard events, only statistical forecasts, such as an El Niño event probability for the next year of 60% can be made. In addition, uncertainties within the social components complicate the prediction of the hazard consequences. These include the reaction of the population to warnings and hazardous events, and the functioning of evacuation plans and general disaster management. Baum and Godt (2009) provide interesting examples where people were moving into warning areas on purpose to secure their homes or save pets. Others misunderstand the warning and believe that if a warning is issued by for example the Department of Forestry it only relates to areas with actual logging activities.

Moreover, the costs of unnecessary evacuations due to false alarms are a major concern for decision makers. False alarms are a problem of early warning systems as they can substantially compromise the credibility of early warning systems (Larsen 2008). In 1982 the United States Geological Survey (USGS) issued a warning for the Mammoth Lakes Area because of an expected volcanic eruption potentially threatening a ski resort on the slopes of the volcano. After the eruption did not occur the USGS was mocked as the US Guessing Society (Die Zeit 2010). However, Sorensen (2000) argues, that false alarms do not necessarily diminish the trust in early warning systems if the reason for the false alarm is understood. The number of false alarms can be reduced by pursuing a conservative strategy and by issuing generalised warnings. However, the use of generalised warnings decreases with the size of the geographic area (Larsen 2008).

An interesting example of consequences of false warning took place in Italy in 2009 were a scientist had been measuring the emissions of radon gases which are associated with earthquakes. Based on his measurements he was expecting a major earthquake for the city of Sulmona two days before the devastating L'Aquila earthquake (5.8 magnitude on Richter scale) which is located 70 km north-west. As his prediction did not turn out to be accurate he was accused for creating panic but later absolved (Die Zeit 2010).

On the other hand a group of seven Italian earthquake scientists who were assessing the seismic activity in the L'Aquila region were accused of gross negligent manslaughter as they failed to predict the disaster. Only days before the earthquake they had stated at a meeting with city officials that there were no grounds for believing a major quake was on the way despite some smaller quakes in the previous days (Cartlidge 2010). The allegations gained much attention in the scientific community as well as from general public, and a petition to end the investigations had been signed by over 5000 scientists. In this open letter it was stated that at the moment there are no scientific method to predict earthquake timing and that therefore, there is no ground for the allegations (Die Zeit 2010). Warner Marzocchi, chief scientist at the Italian National Institute for Geophysics and Vulcanology commented that "*as scientists, we have to focus on giving the best kind of scientific information*" and that the decisions of what actions need to be taken "*is down to others to decide*" (Cartlidge 2010). Thomas Jordan, earth scientists who had also been working in the L'Aquila region added that the costs of false alarms are too high compared to the low probabilities of an earthquake occurring, so that there was no basis to initiate actions such as mass evacuations (Cartlidge 2010).

A similar case happened in the Italian community of Sarno, which was hit by devastating landslides and a debris flood in 1998. Before the disaster event the mayor had told the people to stay calm and to stay at home even though there were already heavy rainfall and landslides occurring in the vicinity of the town (Die Zeit 2010). After the event he was accused for negligent manslaughter but later absolved because the event could not have been foreseen.

The previous examples clearly illustrate some of the problems and challenges of early warning systems, arising from both natural and social components. Besides technical difficulties of natural hazard prediction, legal, social and political dimensions add to the complexity of early warning. Effective early warning systems must therefore be carefully planned. Resulting from the work of the Integrative Landslide Early Warning Systems (ILEWS) project, issues have been identified that need to be addressed when early warning systems are to be installed (Bell et al. 2010). Important factors to be accounted for include the process (flood, volcanic eruptions, landslides), time (slowly developing or rapidly initiating hazards), forewarn time needed to provide useful warning, financial aspects (private or public investments), communication of warning (unidirectional, bidirectional), threatened human lives and infrastructure (cost-effectiveness) and stakeholders to be warned (governmental agencies, emergency services). Thus, early warning systems have to be demand-orientated and adapted to local conditions (Twigg 2003). In addition, it is important that early warning systems are embedded into the local community to increase acceptance of warnings (Mileti 1999; Greiving and Glade 2011).

Given the variety of hazards for which early warning systems have been installed it is difficult to define clear categories. Some basic distinction, however, can be made (Bell et al. 2010):

- Monitoring systems are primarily installed to increase the understanding of natural processes but can also be utilised to plan further actions. These monitoring systems differ by technologies applied, time intervals between measurements and degree of automation.
- Expert- or control systems provide information on potentially hazardous events and are chiefly implemented to gain information on critical developments and with the aim to guide scientists and decision makers.
- Alarm systems are based on monitoring systems and provoke an automatic warning if, for example, a predefined threshold is exceeded. Further differentiation of alarm systems can be made between pre- and post event systems and the forewarn time provided by the system. Moreover, these systems differ in

their degree of integration of social aspects between purely technical applications and integrative early warning systems.

Early warning systems have also been applied for landslide processes, e.g. rotational and translational slides, debris flows and rock slides. Landslide early warning systems can be installed for single slopes, but also for entire regions. Also global landslide early warning systems have been proposed by applying methods such as rainfall intensity and duration thresholds (Guzzetti et al. 2008) or satellite-based InSAR monitoring and progressive failure analysis (Petley et al. 2002).

Regional landslide early warning systems can only issue warnings, such as a 70% probability of debris occurrence for a certain region; single slopes cannot be identified (Wieczorek and Glade 2005). However, local or site-specific landslide early warning systems provide another quality of information. Exceedance of critical thresholds may automatically lead to protective actions, such as alarms, road and bridge closures, evacuation and further disaster management actions. Local landslide early warning systems have been frequently applied, partly because they can sometimes replace structural measures of slope stabilisation while providing sufficient protection (Palm et al. 2003). Site-specific systems generally apply monitoring systems for slope movement or landslide triggering factors such as rainfall and pore water pressure (see Sect. 2.2) as the early basis of warning.

One of the first modern landslide early warning systems was installed in 1984 in Utah, USA, after significant damage by debris flows initiated by snow melt (Baum 2007). Initially, monitoring of precipitation, temperature and slope movement on potential landslides were used to alert local officials and issue a regional debris flow early warning. Later works of (Ashland 2003) established groundwater thresholds for instrumented potential landslides. Regional thresholds were determined based on annual cumulative rainfall. Recent developments include snow monitoring to account for landslide triggering by snow-melt (Baum 2007).

Based on the works of Campbell (1975), who established landslide and debris flow triggering rainfall thresholds by intensity and duration analysis, a regional debris flow early warning system was set up for the San Francisco Bay Area, USA in 1986 (Keefer et al. 1987; Wilson 2005). The system was developed and implemented as cooperation between USGS and National Weather Service (NWS). Quantitative weather forecasts issued by NWS two times a day for the upcoming 24 h were provided to the Landslide Initiation and Warning Project of USGS. Rainfall forecasts were combined with data from automatic rainfall gauges and consequently checked against pre-defined thresholds. Estimation of hazard level and final decision upon warning was assessed cooperatively by experts from USGS and NWS. Initially, triggering thresholds based on rainfall intensity in relation to annual rainfall (Cannon and Ellen 1988) were utilised. Later thresholds were adjusted to account for water storage capacity (Wieczorek 1987) and minimum thresholds for debris initiation (Wilson et al. 1993). Below the minimum rainfall threshold debris flow occurrences are unlikely while above the upper threshold significant debris initiation in the region can be expected. In 1992 it was attempted to integrate radar data into the early warning system to improve the spatial resolution of rainfall measurement. However, integration failed because no reliable relations between radar reflectivity and ground based measurement could be established. Along with technical problems the social aspects were a major challenge for the early warning system. For instance, NWS and USGS had different expectations to the technical system. While USGS interpreted the system as an experimental prototype of which warnings are by-products, NWS demanded reliable predictions and warnings. Warning communication was another challenge for the early warning system. USGS considered early warning as an entirely technical system which ended with issuing an alarm. The population was expected to react appropriately by avoiding dangerous areas. Yet, the population and also emergency services were mostly unaware of debris hazards and their damage potential. In reality, many people intentionally drove into hazardous areas in severe storm conditions trying to get home to save the house or feed a pet (Wilson 2005). Eventually, the system was shut down in 1995 because USGS could not afford to continue the service.

Based on the experiences in the San Francisco Bay Area, USGS and National Oceanic and Atmospheric Administration (NOAA) cooperatively initiated a regional landslide early warning system for burned areas in south California, which are prone to debris flow initiation (NOAA-USGS Debris Flow Task Force 2005). An assessment of potential end-users and their demands towards landslide early warning were clarified before the system was set-up. Alert level terminology was overtaken from NWS severe weather forecasts to increase the acceptance of the population. Dissemination of information and warning communication were adjusted to end-users needs. USGS also developed an education program for involved meteorologists and interested public to explain hydrological characteristics of debris flow initiation in areas with burned vegetation (e.g., California Geological Survey 2003). Technical advances compared to the previous system comprise improved quantitative rainfall forecasts, and implementation of test areas to improve the understanding of triggering groundwater conditions. In addition, empirical and physically-based models were applied to assess susceptibility to debris flows, their potential volume and run-out distance (NOAA-USGS Debris Flow Task Force 2005).

Another regional debris flow early warning system for Oregon, USA, was developed and implemented as a cooperation between Oregon Departments of Forestry (ODF), Transportation (ODOT) and Geology and Mineral Industry (DOGAMI) with Oregon Emergency Management (OEM) (Baum 2007). During periods of intense rainfall meteorologists of ODF monitor measured rainfall and forecasts and assess current hazard level together with geotechnicians which are available 24 h a day. Warning messages are issued if thresholds are almost reached or exceeded. Thresholds used within the system account for rainfall intensity and duration, but are modified in case of significant antecedent rainfall or snow melting. Warning is spread via the emergency channel of the National Weather Service. Within the developed system information and education on debris flow hazards and early warning are also addressed by for example, warning signs along the highway, advise to homeowners and information on websites (Burns et al. 2008; Oregon Department of Geology and Mineral Industry 2010).

A regional early warning system for shallow landslides is implemented for the Seattle Area, USA since 2002 (Baum et al. 2005a; Baum and Godt 2009) and is jointly managed by NWS, USGS and the city of Seattle. The technical system comprises a total number of 17 automatic rain gauges with an average distance of 2–5 km between them and quantitative weather forecasts. In addition, a test slope was instrumented to improve understanding of pore water pressure development and landslide triggering. Furthermore, landslide mapping and probabilistic regional hazard modelling were performed (Baum et al. 2005b). Detailed examination of rainfall data led to the establishment of a minimum threshold for landslide triggering based on intensity and duration analysis and an antecedent water index calculated from cumulative rainfall of 3 days, and rain within the previous 15 days (Chleborad 2000, 2003, 2006). For the assignment of alert levels thresholds are used for both, intensity-duration and antecedent water index. Rainfall exceeding intensity-duration thresholds triggers a warning status at high antecedent water status. Watch level is issued, in the occurrence of medium antecedent rainfall index values and observed or forecasted rainfalls above thresholds. Outlook level is activated if any of the rainfall threshold is exceeded. In other cases the alert is null. In addition, warnings are only provided if thresholds are exceeded for at least three gauges relating to an expected number of three or more landslide events (Baum and Godt 2009). Warning thresholds performed satisfactory in back-analysis with data from the 1978 to 2003 period; only eight storms caused landslides without previous threshold exceedance (Godt et al. 2006). Forty per cent of all warnings were followed by landslides events and 85% off all landslides were triggered by rainfall above thresholds values. To increase the acceptance of the early warning system and improve risk awareness of the local residents, USGS provides educational material and information (USGS 2006).

In the USA, USGS is responsible for allocation of warnings related to geological events, including landslides. To increase interoperability of warning systems and ensure smooth warning communication a common alerting protocol (CAP) was created (Highland and Gori 2008). This data format is the same for many different kinds of warnings including also man-made hazards and terrorism. Today it is widely used by state agencies in the USA. Landslide related CAP warning have been adopted for all study areas, for which reliable rainfall thresholds have been established, i.e. Seattle, San Francisco Bay Area and burned areas and parts of the Appalachian mountain areas of the eastern US. All alerts, including archived warnings, are presented on USGS website. To increase the populations' awareness of landslide hazards and the potential outcomes of landslide events, a documentary movie was produced, which is also planned for school education (Highland and Gori 2008). Moreover, a wide range of fact sheets, reports and other information on landslide hazards, consequences and warnings is produced by USGS.

The most advanced and successful landslide early warning system may be that installed in Hong Kong, China (Schuster and Highland 2007). Hong Kong is densely populated by seven million inhabitants and very prone to landslides occurrences and damage consequences. The terrain is rugged, with hills rising up

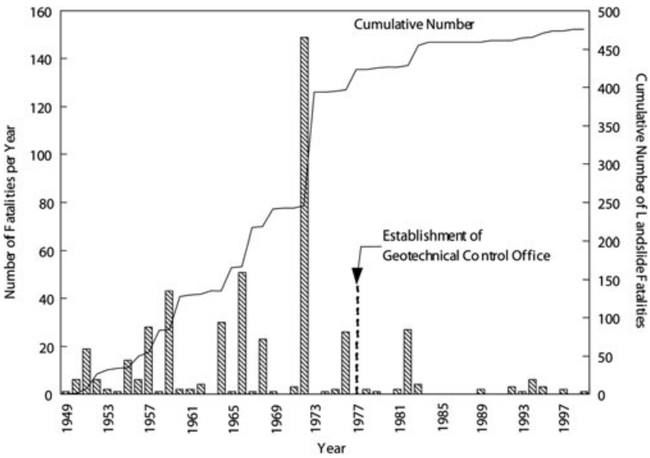

Fig. 2.8 Number of landslide fatalities in Hong Kong (after Wong and Ho 2000)

steeply, and less than 30% of the densely populated areas are flat (0–5°) (Brand et al. 1984). The limited availability of favourable land means that geotechnical slope construction works including design of cut and fill slopes and slope stabilisation are frequently required. Moreover, strong rainfalls with hourly intensities exceeding 150 mm occur along with tropical cyclones and low pressure. After two catastrophic landslide events in 1972 and 1976 which together caused more than 100 fatalities, the Geotechnical Control Office was established to reduce landslide consequences (Malone 1997). Later, the agency was renamed the Geotechnical Engineering Office (GEO). GEO has many responsibilities, such as establishing instructions and guidelines for slope design, slope stabilisation, quantitative risk management and early warning (Chan 2007). Moreover, education programs for the general population and homeowners aim to raise awareness of landslides and related risks. Radio and television features, a telephone hotline and a website provide a wide range of information and advice to local residents (Massey et al. 2001). Detailed information on integrative landslide risk management strategies in Hong Kong and the efforts and experiences of GEO is available in a collection of scientific papers published for the 30th anniversary of GEO (Geotechnical Engineering Office 2007). The great success of slope safety in Hong Kong is also illustrated by significantly lower fatalities due to landslides after the establishment of GEO's predecessor in 1977 (Fig. 2.8).

The Hong Kong regional landslide early warning system was launched in 1977 and is managed cooperatively by GEO and Hong Kong Observatory. More than 100 automatic rain gauges built the technical base for early warning. Rainfall thresholds triggering landslides in Hong Kong were first established by Lumb (1975), but were modified several times afterwards when improved real time rainfall and landslide data became available. Initially, warning thresholds accounted for cumulative 24 h rainfall in relation to rainfall of the preceding

15 days. Warnings were issued if measured rainfall of the last 20 h and the forecasted rain for the next 4 h exceed 175 mm (Chan et al. 2003). In the 1980s an hourly rainfall threshold of 70 mm was added to the warning scheme. Progressive analysis of landslide initiation and related rainfall events led to prediction of the number of landslides expected for certain storm events. Warnings were only issued if 15 or more landslides were expected to occur (Chan et al. 2003). Since 2003 a GIS-based approach has been used for landslide prediction (Yu et al. 2004). Therein, the entire area of Hong Kong is represented as grid cells accounting for number of properties contained on the slopes. The number of expected landslides is then modelled according to a spatially variable susceptibility to slope failure. A recent development of the landslide early warning system includes the integration of radar data from the SWIRLS system (Short-range Warning of Intense Rainstorms in Localised Systems) to track storm cells and improve quantitative prediction of localised storms (Cheung et al. 2006). Warning dissemination utilises TV, radio and internet to inform the public. In addition, emergency forces and hospitals are contacted if large numbers of landslide are expected. In early years warning messages were mostly aimed at slum dwellers because they lived in most hazardous areas. However, social and geotechnical developments since the 1980s changed the focus. Today, the intention of early warning is to inform the entire population about potentially hazardous events, thus to provoke cautious behaviour.

Mainland China is probably experiencing the highest landslide damage and number of fatalities in the world (Tianchi 1994). China has begun to address the landslide problem in the 1990s by starting a nationwide investigation program including landslide mapping, susceptibility zoning, risk analysis, rainfall threshold analysis, prevention planning and engineering counter measures (Yin 2009) and early warning (Zhou and Chen 2005). Since 2003 landslide warning based on rainfall forecasts are issued after general weather reports on prime time TV shows (Yin 2009).

A regional landslide early warning system based on susceptibility maps and rainfall thresholds was installed for Zhejiang Province (Kunlong et al. 2007; Eng et al. 2009). The system is based on rainfall forecasts and works as a WebGIS. Warnings are issued if rainfall predictions exceed one of the two defined thresholds and near real-time warnings are spread through various communication channels (internet, telephone, etc.). The warning system is also combined with an assessment of economical risks which aim to extend the system to landslide risk warning (Wu et al. 2009).

Zhong et al. (2009) provide detailed information of the precipitation based early warning system for Hubei Province. The landslide early warning system was installed in 2006 and represents a WebGIS. Critical rainfall thresholds have been determined by analysing the statistic relationship between spatial distribution of occurred landslides and rainfall data. Warning generation is based on 2 and 15 day antecedent rainfall, which is compared to 24 h rainfall forecast. If thresholds are exceeded in any of the 82 divisions in which Hubei is differentiated, the Meteorological Survey of Hubei Province issues a warning on the internet. More information on the current situation is freely accessible in the form of maps on the internet. In three years of operation the system issued 11 warnings, of which 6 were followed by landslide events (Zhong et al. 2009).

The Geotechnical Engineering Office of Rio de Janeiro, Brazil, implemented a regional landslide early warning based on rainfall thresholds and rainfall monitoring in 1996 (Ortigao et al. 2002; Ortigao and Justi 2004). In early years the early warning system was not entirely automated which resulted in a lack of warnings on for example, weekends and holidays, as no experts were available (D'Orsi et al. 2004). Instead, automated fax messages were sent without proper data analysis. However, due to wide acceptance of the early warning system it was expanded in 1998, and since then provides continuous service. At the same time a rainfall radar was included into the technical input to increase forewarn time. In addition, a test slope was equipped with piezometers and inclinometers to gain more insights into the failure processes. However, it was decided not to establish more site-specific monitoring systems as the costs were too high. Two critical rainfall thresholds were determined which relate hourly rainfall intensity to accumulated rainfall for 24 and 96 h (D'Orsi 2006). Four warning levels are used, e.g., low (landslides could happen), medium (occasional landslides), high (scattered landslides) and very high (generalized landsliding). Current information on warning levels is broadcasted by media and is also available online. In addition, emergency services are informed by fax to prepare for potential landslide events. In addition to the landslide early warning system, flash floods were later integrated into forecasting activities (D'Orsi 2006).

A regional debris flow early warning system was installed in Combeima-Tolima Region in Colombia (Huggel et al. 2008; Huggel et al. 2009). The project was initiated by the Swiss Agency for Development and Cooperation (SDC) which promoted investment into early warning, risk awareness education and disaster prevention training instead of solely focussing on reconstruction. The automatic technical monitoring system includes three rainfall stations and a series of geophones. At the Regional Emergency Committee Centre data is collected and analysed 24 h a day and is available online. Rainfall thresholds initiating debris flows were calculated based on intensity and duration, and with respect to antecedent rainfall up to 30 days. If thresholds are exceeded an emergency plan determines actions to be taken. Interestingly, Huggel et al. (2009) analyse the performance of the developed system by a cost-effectiveness calculation based on historic records. Therein, the costs of false alarms are compared to losses in case of hazard events which can be used to adjust rainfall thresholds. However, this approach is ethically questionable as it requires definition of monetary costs of lost human lives.

The combined hydrology and slope stability model CHASM, which is applied within this study, has also been used in another landslide early warning system. However, instead of applying CHASM for continuous modelling of slope stability, rainfall thresholds previously calculated were validated by detailed analyses for single slopes. The system is located along the Kuala Lumpur Highway, Malaysia, and is in service since 1996 (Lloyd et al. 2001). An automated monitoring system measures rainfall intensity which is compared to pre-defined threshold values also

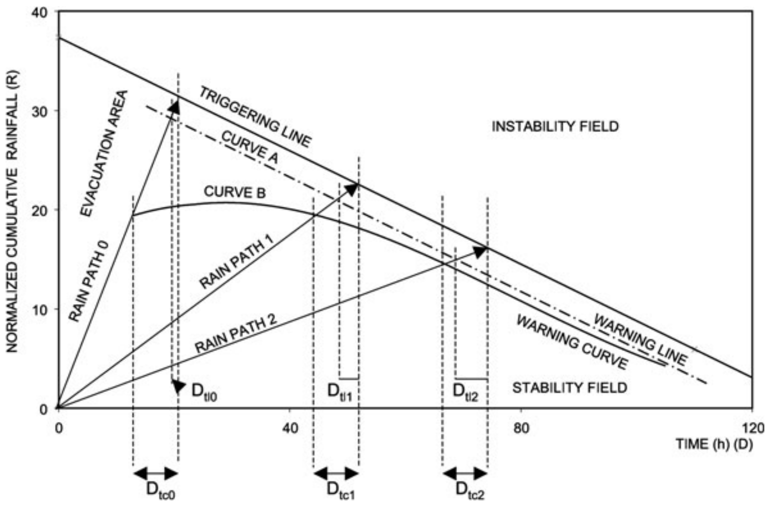

Fig. 2.9 Comparison of warning curve and warning line thresholds and subsequent time spans for evacuation (after Aleotti 2004)

accounting for antecedent rainfall conditions. A series of single slope CHASM simulations illustrated the effect of high soil permeability on slope stability. In conclusion, rainfall longer than 6 days ago did not significantly influence slope stability and could be neglected in rainfall threshold determination in the study area.

An extensive early warning system for debris flows in Indonesia is presented by Apip et al. (2009, 2010). Based on local rainfall threshold analyses accounting for rainfall intensity and duration, as well as antecedent rainfall, design charts were created which provide three warning levels (safe, watch, danger). Moreover, it is tried to widen predictive power of the warning system by integrating spatially distributed modelling of slope stability with physically-based hydrology and stability model. Therein, quantitative rainfall forecasts by National Oceanic and Atmospheric Administration (NOAA) are utilised for real-time modelling of potential landslide initiation. In addition, the model is planned to be further developed to provide forecasts of river flows, sediment transport and debris flow run out.

A similar approach to early warning is provided by Liao et al. (2010), who also worked on regional landslide early warning in Indonesia. The proposed system includes a physically-based hydrology and slope stability model, as well as integration of quantitative rainfall forecasts. Modelling is performed in two steps. Initial calculations provide hot spots, which can then be modelled using data with higher resolution. However, the technical system represents a prototype development and further research has to be accomplished in order to increase its predictive capacities.

Schmidt et al. (2008) present an innovative landslide early warning system for New Zealand. Therein, probability of landslide failures is computed by combination of a regional physical-based hydrology and stability model with quantitative weather forecasts. However, landslide prediction is subject to large uncertainties which are assessed by probabilistic methods. Unfortunately, the early warning system was only a prototypic development and is currently not active.

Aleotti (2004) presents a prototype of a regional landslide early warning system for shallow landslides in the Piedmont Region of north-western Italy. Rainfall thresholds were determined by analysing intensity-duration, antecedent rainfall and mean annual precipitation. Warning thresholds, however, were established lower than triggering thresholds to provide more safety. Instead of a warning threshold parallel to the triggering threshold (Aleotti 2004) applied a curve to account for different rain paths (Fig. 2.9). By doing so time spans until landslide triggering threshold exceedance are integrated, which are important for initiation of evacuations. The technical warning system includes rainfall forecasts and station measurements. The system remains in an ordinary attention state until thresholds are exceeded by rainfall forecasts. A preceding warning procedure is launched if landslide prone areas are affected by threshold exceedance. Rainfall paths are then plotted according to antecedent and real-time rainfall and an alert is issued according to the pre-defined thresholds.

Recent developments of the regional landslide early warning system concentrated on the improvement of thresholds by including local properties, such as topography and geological properties (Tiranti and Rabuffetti 2010). Consequently, three thresholds were established, i.e. regional, sub-regional and a pragmatic threshold, which accounts for multiple occurrences of landslide in single rain events. All thresholds were tested for their performance in a back-analysis in terms of correct, false and missed alarms. In addition, a technical system named SMART was developed which analyses rainfall time series for each rain gauge in real time and identifies where thresholds are exceeded. The current early warning system utilises rainfall forecast and real-time measurements and applies the pragmatic threshold (Tiranti and Rabuffetti 2010).

The Åknes rockslide in Norway is one of the most intensely investigated and monitored landslides worldwide (e.g., Derron et al. 2005; Ganerød et al. 2008; Kveldsvik et al. 2008, 2009; Eidsvig et al. 2011; Heincke et al. 2010; Grøneng et al. 2010). The rockslide itself does not pose direct threat to a community, however, slope failure is supposed to trigger a tsunami affecting ships and towns along the fjord. The rockslide mass has a volume of 30–40 million m^3 and displacements vary with seasons and reach 3–10 cm/year with daily movements up to 1 mm (Blikra 2008). The technical monitoring system includes extensometers, inclinometers, crackmeters, tiltmeters, geophones, piezometers, automated measurements by theodolites, laser and GPS and ground based radar, and a climate station. All data is available in a web-based database and supervised by experts 24 h a day. Threshold values for displacement velocity have been established which relate to five alert levels colour-coded from green to red. In case of imminent slope failure sirens warn the population in potentially affected towns.

Fig. 2.10 Early warning system at Winkelgrat landslide equipped with automatic extensometers (*left*) and traffic light for road closure (*right*)

Other topics of the project include development and implementation of warning routines and evacuation planning (Blikra 2008).

Another example of an intensely monitored rock slide is the Frank Slide at Turtle Mountain, Canada, which exhibited a catastrophic failure in 1903 causing 70 fatalities (Froese et al. 2005). A landslide monitoring and early warning program was launched in 2003 and commenced with detailed site investigations using InSAR, microseismic surveys, ground penetrating radar, drilling and core sample analysis. Within the actual early warning system tiltmeters, extensometers and crack meters are used as primary sensors as they provide high detail displacement data (Froese et al. 2006). Secondary sensors include differential GPS and automatic theodolite measurements which have higher fluctuations but improve understanding of the overall situation. Background information is gained by tertiary sensors, i.e. climate station data and microseismic monitoring. The early warning system comprises four elements (Froese et al. 2005). A monitoring procedure was established to determine responsibilities for measurements and their frequencies, which might change in response to trends and anomalies in the data. Within the threshold development procedure value-based and velocity-based thresholds two standard deviations above noise level were established. Development of alert levels and notification protocols comprise the third element of the early warning system. A standardised terminology and appropriate response to trends in monitoring data were determined. Moreover, action advice was developed for emergencies including procedures for communication and evacuation. The current alert level is accessible on the internet and is presented in four colours. The green alert level indicates normal situations where measurements are in the range of background noise but may exhibit seasonal fluctuation. The watch level is active if multiple sensors display unusual trends and leads to direct communication between technical experts and local decision makers and municipal officials). The warning level is initiated if multiple sensors demonstrate acceleration trends exceeding pre-defined thresholds. If several sensors indicate accelerations and final failure is imminent (one to three days to failure) then the alarm level is issued and the emergency response procedure is executed. More detailed information on monitoring (Read et al. 2005), modelling (Froese et al. 2009) and the information platform (Froese et al. 2006) is given in the respective literature.

An early warning system for rockfall is installed at the Winkelgrat, also located at the Swabian Alb in Germany (Fig. 2.10). The technical system consists of nine automatic extensometers installed in 2002 (Ruch 2009). An automatic alarm message is sent to the local emergency service if pre-defined thresholds are exceeded. The road below the unstable rock mass is then closed by setting two traffic lights to red to prevent cars from entering the hazardous area. At the same time road maintenance service, police, rescue forces and the regional geological department are informed via SMS and fax. Following field investigations by experts of the regional geological department it is decided to initiate further protective measures, or in case of false alarms, to reopen the road (GEOSENS 2009; Krause 2009).

Another landslide early warning system in Germany is described by Lauterbach et al. (2002) and Krauter et al. (2007). This system relies primarily on technical solutions, for example, GPS displacement measurements, and is installed at an autobahn in south-west Germany. The slope under investigation is known to cause deformations to the road surface since the 1960s. The landslide mass is calculated to be 700,000 m^3 with average annual movement rates of 1–2 cm. As structural measures were considered uneconomical a GPS based warning system was installed. The system consists of 5 measured points of which the main station is based outside the landslide mass. Accuracy of the system is about 1 mm in location, and 2–3 mm in height. Two kinds of alarms are implemented: one occurs when obviously false measurements are being taken or maintenance works are necessary, the other if pre-defined thresholds of movement rates are exceeded. If warning thresholds are exceeded the experts operating the system are informed via automatic telephone calls and immediately check the situation in the field, which then can lead to emergency actions like, for example, road closure.

Several slope monitoring and early warning systems have been installed in the United Kingdom. An extensive technical monitoring and early warning was installed for the coastal landslides on the Isle of Wight (Clark et al. 1996) where the first tiltmeter slope early warning started in 1981 (Barton and McCosker 2000). Today, the technical system comprises monitoring of surface and subsurface movements by theodolites, GPS, inclinometers, tiltmeters and crackmeters. Weather stations and piezometers record also rainfall and its effect on landslide triggering. Automatic alarms are issued if pre-defined displacement thresholds are exceeded. Automatic monitoring systems were preferred over manual systems even though initial costs are considerably higher. Similar technical monitoring systems have also been installed in Lyme Regis, Scarborough and Cromer (Clark et al. 1996).

In Lyme Regis a series of inclinometers, piezometers and GPS ground markers are continuously monitored and provide an alarm to experts and decision makers if an imminent threat is given (Clark et al. 2000). In addition, an increased monitoring frequency can be initiated and emergency response is prepared.

At Cromer, automatic readings of field sensors activate an alarm by sending a message by pager. Warning thresholds are based on a pre-determined movement velocity of 3 mm per hour or 10 mm in 6 h.

Landslide early warning on the Isle of Wight is part of an extensive general coastal management scheme by the Isle of Wight Centre for Coastal Environment which promotes a holistic approach. Coastal management comprises for example, allocation of planning guidance maps, building codes, engineering measures, monitoring, forecasting and early warning. A wide range of information is available on the websites (Isle of Wight Centre for the Coastal Environment 2010), such as a best practice guide (McInnes 2000) providing detailed descriptions of monitoring and warning schemes, as well as advice to homeowners on how to reduce risk of coastal erosion and instability. In addition, the local management and information centre arranges workshops and educational field trips.

An extensive technical monitoring system is installed along the slopes of Clyde Dam Reservoir, New Zealand (Macfarlane et al. 1996). More than 5,500 theodolite observation points were installed to monitor displacements during dam construction and reservoir filling. After filling was accomplished the number of observation points was reduced. Further monitoring equipment includes borehole extensometers and inclinometers for subsurface movements and piezometers for slope hydrology. All data is automatically stored in a database and alarms are raised automatically if pre-defined thresholds are exceeded.

Given the great number of engineering works in China many applications of monitoring and early warning systems are described in the literature. Since the 1990s much attention has been paid to the landslide hazards along the Three Gorges Dam Reservoir, China, and many investigations have been performed by researchers on this emerging topic (Fourniadis et al. 2007a, b; Li et al. 2008; Wang et al. 2008c; Jian et al. 2009; Li et al. 2009a, b; Yin 2009). Several landslide monitoring and early warning systems are located along the lake created by the Three Gorges Dam. One of these was installed for the Shuping landslide, a reactivated mass movement which accelerated after the impoundment of the lake. Several extensometers are used to measure the landslide (Wang et al. 2008b; Wang et al. 2009). Dai et al. (2008) describe a monitoring and warning system based on high resolution optical fibres for the Yuhuangge landslide in the Three Gorges Area. Four alert levels were determined which account for changes in velocity and pore water pressure. Local decision makers are informed about current alert levels and are obliged to issue final warnings and initiate evacuation. Since 2004 the alert level was once set to yellow level due to significant acceleration and damage on infrastructure (Yin et al. 2010a). Later however, displacement rates decreased to former values and the alert level was subsequently lowered.

Moreover, several more interesting papers on applied landslide early warning systems in China have been published, unfortunately, many are only available in Chinese language with English abstracts (Jiang et al. 2009; Xu and Zeng 2009; Ye et al. 2009).

The Illgraben catchment (9.5 km^2) in Switzerland has some one of the highest debris-flow activity in the Alps. A monitoring and early warning system for debris flows was installed and described in detail by Badoux et al. (2009). The overarching early warning concepts includes ongoing education and allocation of information for the local population regarding debris flows and possible consequences, a monitoring system, repeated field surveys to assess changes in the catchment, and integration of meteorological measurements to increase forewarn time (Graf et al. 2006). Several education campaigns were performed to inform local population about potential hazards and the early warning systems. In addition, children at elementary level learn about debris flows in school. Tourists are provided information at local tourist information centre. Along the debris flow channel warning signs were put up every 200 m explaining the threat of debris flow occurrences in five languages. Moreover, warning lights and loud speakers were installed at three spots where hiking trails cross the debris flow channel. The early warning system is managed and maintained by Illgraben Security Commission and contacts local emergency task forces if potentially dangerous situations emerge. The technical system includes several geophones located at check dams, which can automatically trigger warning lights and speakers further down the debris channel if a seismic signal lasts for more than five seconds. At the same time SMS and emails are sent to local decision makers. A forewarn time of 5 to 15 min between measurement of debris flow by geophones and a debris flow reaching settlement areas in the valley is provided by the system. Alarms can be cancelled if geophones further downslope do not detect seismic signals 10 min after the first signal. This is done to decrease chances of false alarms due to other potential geophone triggers, e.g., rock fall, thunderstorms or earthquakes. Further technical equipment of the Illgraben monitoring systems includes measurement of discharge by ultrasonic sensors, laser and radar. Based on their experiences Badoux et al. (2009) propose radar as the most suitable method for early warning, as it provides smooth and reliable data on discharge even in situations of rapidly fluctuating discharge amounts. The catchment is visited and mapped regularly to detect changes in the debris flow source area, such as landslides that provide material for further debris flow occurrences. Including meteorological forecasts into the early warning systems and defining rainfall thresholds was also trialled. However, integration failed because local thunderstorms in alpine areas are difficult to predict. The debris flow early warning system at the Illgraben can be regarded successful. Since its implementation 20 alarms were issued, of which only one was a false alarms, and in only three cases a warning was cancelled even though the debris flow had not stopped. The Illgraben catchment is also part of the national IFKIS-Hydro early warning and information platform, which provides monitoring data and event documentation (Romang et al. 2010).

In the North Italian community of Nals a local debris flow early warning system was installed after devastating debris flow events in 2000 (Egger and Mair 2009). The aim of the early warning system was to be an addition to structural protection measures. Debris flow material is supplied by landslide processes in the upper catchment. However, due to the high activity it was decided not to install an automatic system there, but to place a series of geophones into the debris flow channel to detect already initiated events. Still, a forewarn time of 20 to 60 min between a geophone alarm and the debris reaching settled areas is accomplished. Further technical equipment includes a piezometer, rainfall stations and a remote controlled video camera with flood lights.

Another Italian case study on a debris flow warning system utilising geophones is presented by Arattano (1999), however, it only was active for one summer.

A prototype of a mudflow early warning system for the Italian city Sarno is described by Sirangelo and Braca (2004). Therein, the probabilistic hydrology model FLaIR (Forecasting of Landslides Induced by Rainfall) was applied, which correlates rainfalls with landslide occurrence. Warning thresholds were established by back analysis and included the large 1998 event. According to these thresholds three warning levels were determined, i.e. attention, alert and alarm.

The same model has been applied to Lanzo Valley of the Piedmont, Italy (Capparelli and Tiranti 2010). Promising performance led to the current implementation of an automatic early warning system.

Hübl (2000) describes the application of a prototypic early warning system for the Wartschenbach catchment in Austria, which frequently experiences debris flows and flash flood events. The developed early warning system is thought as a passive protection measure. The technical system is based on measurement of rainfall and flow discharge by ultrasonic sensors in the upper catchment. If measurements exceed pre-defined thresholds it is up to experts to decide whether to close lower lying roads to prevent cars being hit by debris flows. By developing adequate response plans for hazardous events they have tried to address the response of the local community. The implemented system was planned and implemented as a prototype and should be installed in other catchments which could potentially produce debris flows after a test period.

A novel a landslide early warning system is described by Sakai (2008). Earlier research (Sakai and Tarumi 2000) indicated that concentrations of sodium, calcium and, sulphate ions in groundwater changed before phases of landslide activity. Landslide failures could be predicted up to 90 days in advance. Therefore, a prototypic landslide early warning system was set up which utilises automated ion-selective electrodes to provide early warning to railroads in Japan. Data is transmitted from the sensors in the field to train dispatchers and track maintenance engineers via mobile phone networks. Measurements are taken every 1 to 3 days, but frequency can be increased in the case of unusual sensor readings.

Another example of an early warning system in Japan is presented by Chiba (2009). The warning system strongly emphasises warning communication and is regarded as an integral element of the local disaster prevention program against sediment-related processes (debris flows and debris floods). Earlier research on local hazards provided information on potential hazardous zones and return periods, which was utilised to allocate warning and evacuation zones in the occurrence of debris flow events. Several people were employed to carry out education programs in which local residents were informed about potential hazards and appropriate reactions in case of a warning. If exceedance of pre-defined river flow thresholds occurs a disaster management headquarter is assigned in which all information about the current hazard status is collected. Information is gathered primarily by the employees by calling local residents by cell phone. Moreover, all data is updated to a GIS platform which is available online. Chiba (2009) illustrates the effectiveness of the warning system by comparing its performance to a neighbouring town, in which no early warning system was installed, and no detailed hazard maps and evacuation plans were available. During a debris flow event local disaster managers were overwhelmed by incoming information and no efficient evacuation could be initialised. In contrast, disaster managers of the town with a warning system were able to quickly determine where debris flows had occurred and to initialise evacuation according to the pre-determined schemes.

Flentje et al. (2005) present a real-time monitoring network for time pore water pressure, slope movement and rainfall in Wollongong, Australia, which aims to enhance understanding of landslide triggering process and improve quantitative assessment of landslide hazards. All data is automatically sent via a cell phone network to a web-based database available online. Threshold values have been determined and current measurements are colour-coded to allow for easy interpretation. However, the described system is essentially technical and does not aim to provide warning messages or initiate counter measures or evacuation.

Besides the ILEWS project several other research programs focussing on early warning systems for natural hazards were funded within the Geotechnologien framework. Three of these projects also concentrated on landslide processes, and will briefly be described in the following.

The SLEWS (Sensor-based Early Warning System) project focused on three sensor types measuring acceleration, inclination and pressure to monitor landslide initiation (Fernandez-Steeger et al. 2009). The project emphasized technological developments accounted for sensor development and laboratory testing. A large proportion of the accomplished work concentrated on wireless sensor networks to ensure smooth data transmission. Developed sensors were applied to several real case studies on the Barcolonette earthflow in France, and rockfall warning in Rathen, Germany. However, besides the technical research, the integration of early warning in social decision making process was another topic of the SLEWS project.

The main goal of the alpEWAS project was sensor-based monitoring and early warning in the Bavarian Alps (Singer et al. 2009; Thuro et al. 2009). Thereto, three main methods were utilised to detect displacements, i.e. TDR measurements, prism-less tachymetrie and low-cost GPS measurements. In addition, an information platform was set up to collect all data and inform involved experts by email and SMS if pre-defined thresholds were exceeded.

The EGIFF project adopted a technical approach and concentrated on the development of new methods applicable within landslide early warning. A wide range of geotechnical data for a test slope south of Munich, Germany, was compiled and modelled by a finite element model (Breunig et al. 2009). In addition, 3D/4 D databases were developed for effective data visualisation. Moreover, the project implemented an automated system to interpret media news and extract landslide related information.

From the examples of landslide early warning systems illustrated above some conclusions can be drawn. Regional landslide early warning systems that focus on shallow landslides or debris flows generally rely on rainfall thresholds derived by

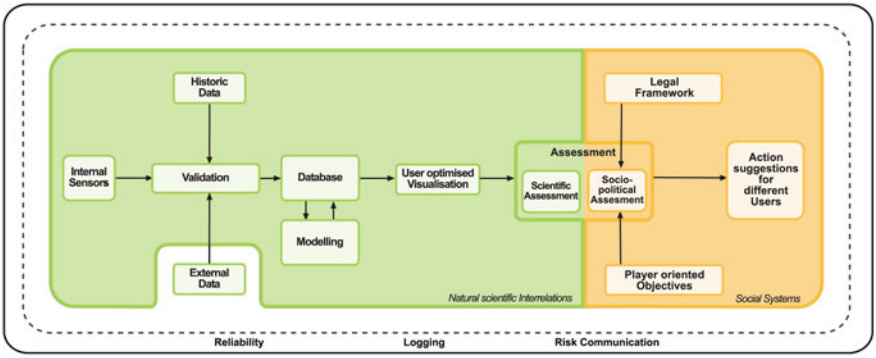

Fig. 2.11 General structure of ILEWS project (Bell et al. 2009)

empirical or physically-based methods. In some cases local test slopes are equipped with monitoring systems to improve understanding of landslide triggering and consequently modify rainfall thresholds. Innovative approaches try to integrate sophisticated slope stability models and real time modelling of landslide initiation Local landslide early warning systems however are installed for a wider range of processes. For debris flows technical early warning systems can be fairly simple because it may take several minutes until an initiated debris flow reaches settled areas. Forewarn time for other landslide processes is often shorter and early warnings are more complex. For deep-seated landslides and failures in rock more complex monitoring is applied to measure displacements and processes related to movement triggering. Warning thresholds may account for displacement or critical parameter values of triggering factors. Modelling of slope behaviour by complex slope stability models is an important part of landslide prediction and is frequently applied for landslide early warning. Most landslide early warning system are not fully automated but leave judgment of the current situation and final warning to experts. Existing landslide early warning systems differ substantially regarding the integration of social aspects. In some cases landslide early warning is integrated into larger schemes for slope safety, risk management, disaster prevention and hazard awareness, while other systems constitute simple technical approaches.

2.5 The ILEWS Project

The work described within this thesis is embedded into the ILEWS project (Integrative Landslide Early Warning Systems) which will be briefly introduced in the following. Integrativity therein does not only refer to a strong interdisciplinary and cooperative work between the project partners, but also to involvement of social sciences aiming to cooperatively embed early warning into the prevalent political structures. Some results are presented in Chap. 7; more detailed information is provided in Bell et al. (2010). The ILEWS project was funded by the German Federal Ministry of Education and Research (BMBF) and integrated into the Geotechnologien research program. The project started in 2007 and ran for three years.

It is important to note that the research carried out in the ILEWS project partly overlaps with the topics of this thesis; however, several aspects are investigated in more detail in this work while other aspects are not covered. While the analysis of slope movement and hydrological monitoring data, and subsequent development of landslide early warning models are main goals of this thesis, the ILEWS project had a wider scope. The overall goal of the ILEWS project was to develop and implement a transferable early warning concept starting with sensors in the field and modelling of early warning, and ending with user-optimized action advice embedded in a holistic risk management strategy. To address the multiple issues arising from such a comprehensive approach project partners from various scientific backgrounds participated in the project, i.e. sensor technology, geoinformation, geomorphology, geodesy, history, social geography and spatial planning. Altogether, 10 research partners cooperated within the ILEWS project, of which five were private companies, and five university research groups. The general structure of the ILEWS project is illustrated in Fig. 2.11.

The project can be distinguished in three clusters, i.e. monitoring, modelling and implementation. However, due to the complex mission of developing and implementing integrative landslide early warning systems and the interlinked workflow of the involved project partners, several tasks were carried out cooperatively.

Within the monitoring cluster the main goals were the prospection, and installation and operation of an adapted monitoring system for hydrology and slope movement on a landslide at the Swabian Alb, South-West Germany. Important milestones of the monitoring cluster include:

- geophysical prospection and development of a technical monitoring system accounting for local geomorphology
- installation of hydrological sensors, inclinometers and geodetic network
- continuous and periodic measurements of hydrology and slope movement
- automated data storage, transmission and web-based visualisation
- development of web-based data management platform allowing for analysis and interpretation
- archival research for analysis of magnitude -frequency characteristics of landslides in the study areas.

The overall goal of the modelling cluster was to analyse the data, and provide reliable information on future slope behaviour based on a range of modelling approaches. Some of the main aims of this cluster were:

- data analysis and validation
- application of empirical-based, physically-based and movement-based models
- integration of models into an early warning system
- modelling of early warning in real-time for both local and regional study areas.

Within the cluster implementation cooperative risk management and end-user optimised warning communication were the main objectives. Other goals include:

- clarification of local and regional demands towards landslide early warning
- integration of warning into the respective social processes of decision making
- cooperative definition of protection goals
- development of alternative risk management strategies.

The objective of ILEWS, to develop and implement an adaptive and integrative landslide early warning concept, was examined by a transfer to two studies of which one is already equipped with a technical system.

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