11 The Influence of Plant Cover Structures on Water Fluxes in Agricultural Landscapes

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Introduction: Water Problems

Water shortages, as well as floods and problems of water quality, especially its pollution by nitrates, have become worldwide threats to the sustainable development of human populations. In many regions of the world, water abstractions exceed available supplies (WMO, 1997).

There is a prevailing premise that the best way to manage water resources is via large-scale technical interventions, such as new dams, aqueducts, pipelines, reservoirs and other devices for water withdrawals, storage, distribution or diversion (Gleick, 2003).

Demand for water grew at more than twice the rate of global population growth in the 20th century, leading to many regional water crises (about 80 countries, constituting 40% of the world's population, showed serious water shortages) and to a situation in which people presently use about half of the world's available fresh water (WMO, 1997).

It is no surprise then that water lies at the heart of many national and international conflicts globally. In an effort to address these problems, the UN Millennium Development Goals calls for a halving of the number of people without access to safe drinking water by 2015. It also calls for the implementation of strategies for sustainable water exploitation. The limited success so far of this initiative has compelled administrations to look for alternative water policies. Besides large water management constructions, so-called 'soft-path solutions' are proposed, which require much lower funding inputs and rely on decentralized decision making and use of more efficient technologies (Gleick, 2003). Stress is placed on the efficiency of water use for sanitation, food production, irrigation and other activities in small enterprises.

In order to develop a strategy for sustainable water management, one has to grasp the system of relationships between the climatic constraints on water balance and the patterns of main water fluxes in landscapes, including the kinetics of water cycling and recycling and its uptake for human populations. Relying only on a single characteristic of a water regime often leads to incorrect conclusions. Thus, for example, the average annual precipitation in Finland amounts to about 550 mm and in Poland to 700 mm, but Poland is a more water-stressed country than Finland because evapotranspiration here is much higher than in Finland. Thus, the amount of precipitated water alone has little informative value for an evaluation of water conditions. Besides already-known technical solutions for water storage and recycling, new options have been provided by the recent advances in landscape ecology (Ryszkowski and Kędziora, 1987; Olejnik and Kędziora, 1991; Ryszkowski *et al.*, 1999; Kędziora and Olejnik, 2002).

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The goal of this chapter is to present recent progress in landscape ecology concerning the influence of plant cover structure on water cycling.

The Influence of Water Shortages on Landscape Structure

Inland ecosystems constitute a major source of renewable freshwater resources. Forests, grasslands, wetlands, lakes and rivers play substantial roles in supplying high-quality water. To perform this service, ecosystems require solar energy to run water cycling and drive the physical and chemical processes characterizing ecosystem properties and to maintain the biochemical reactions supporting plant, microbe and animal life. Water, of course, is essential for the existence of biota. An obvious symptom of water shortages is plant wilting, which reveals the disturbance of plant life processes and may result in the disruption of the photosynthetic reactions on which all heterotrophs – including humans – rely. The ability of water to absorb large amounts of heat determines its significant role in temperature regulation, not only in organisms but also in the environment. Thus, for instance, the evaporation of 1 l of water, i.e. a 1 mm-thick water film over 1 m^2, needs as much energy as is necessary to heat 33 m^3 of air by 60 °C. There are many other physical and chemical properties of water that make it a decisively important factor in the maintenance of various ecosystem functions. If water supplies to ecosystems are undermined, the system is unable to survive and changes to some other state, characterized by other structures and functions.

This chapter posits that growing water shortages in rural areas are an increasingly serious threat to the environment. Substantial grassland losses have been observed in Western Europe, particularly of wet grasslands, all largely due to drainage and agricultural intensification (Stanners and Bourdeau, 1995). More than half of the world's wetlands have been converted to other uses, especially agriculture (Johnson *et al.*, 2001). Poland, like eastern Germany and Hungary, is the most water-stressed country in central and Eastern Europe. The mean annual precipitation for the whole country is equal to 700 mm estimated corrected value, which is the value of precipitation observed in gauges and corrected for evaporation and wind effect. In the central part of Poland, about 80% of precipitation is used for evapotranspiration, which means that annually available water resources for sectoral abstractions are very low. Such a situation indicates a very tight water balance, and even small variations in the ratio of water precipitation to evapotranspiration could have large ecological or economic consequences.

The low discharge resulting from such a water balance delimits the areas of surface water shortages, which amounts to 120,000 km^2 (38% of Poland's total area). In the area located in the Central Plains, the mean annual runoff is less than 2 $l/s/km^2$ (Kleczkowski and Mikulski, 1995). Thus, the Central Plains is an area that is very seriously threatened by water shortages. The Wielkopolska region, located in the western part of the Central Plains, has been recognized as the most severely affected in the water shortage area. According to studies carried out by Kaniecki (1991), the region's total lake area decreased by 12.9% between 1890 and 1980, and 30 lakes disappeared completely. Very high disappearance rates were detected for small ponds. Out of 11,068 small water reservoirs found on the maps produced in 1890, Kaniecki could detect only 22.5% in the 1960s. Drainage work carried out in this period triggered drying processes that were facilitated by the very tight water balance in these regions.

The process of land drying is also reflected in changes to plant communities. Czubiñski (1956) found that, in the Wielkopolska region, xerothermic plant species (i.e. those tolerant of dry conditions) made up 14% of the total of all vascular plants, while in more humid areas, located in the East Mazurian region, xerothermic species made up less than 7% of the total flora. Denisiuk *et al.* (1992) analysed changes in the distribution of wet (flooded for a few months), humid (flooded for a couple weeks) and dry (never flooded) grasslands. They found a dramatic conversion of wet to dry grasslands during a 19-year period (from 1970 to 1989) in some regions of Poland (Fig. 11.1). About 126,000 ha of grassland disappeared during the period.

Another phenomenon connected with the progressive local lowering of the groundwater

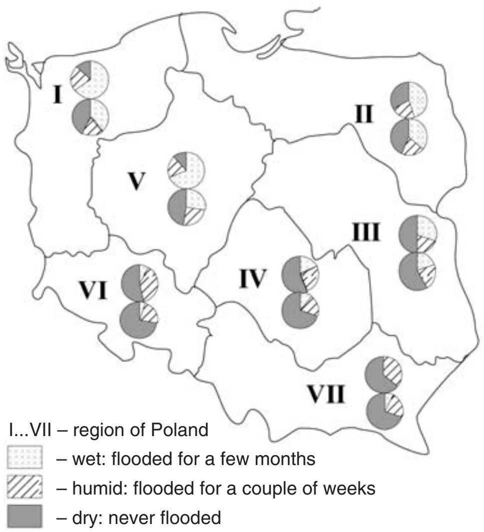

Fig. 11.1. Changes in Polish grassland area, 1970–1989.

table in Wielkopolska region has been the transformation of meadows into arable fields. During the first half of the 20th century, about 20% of meadows in the Prosna River valley were ploughed and the hay yield in the remaining meadows dropped in the same period from 4.0 to 1.2 t/ha (Grynia, 1962). The same author found that low-moor drying along Wielkopolska's main rivers (Noteæ, Warta, Obra) led to the loss of phosphorus and potassium, which in turn contributed to the transformation of productive riparian plant communities into low productivity grasslands (the Malinia Meadows), yielding a single hay harvest.

Thus, speeding up water removal by drainage when the water balance is characterized by high rates of evapotranspiration transforms ecosystems into less productive ones. In Denmark (Southern Jutland) 27% of ponds disappeared between 1954 and 1984 due to agriculture (Bülow-Olsen, 1988). The same trends are observed in other countries.

The loss of small water reservoirs impairs landscape water-storage capacity. Small field reservoirs not only store water in their beds but also increase retention in the soil surrounding ponds (Kędziora and Olejnik, 2002). Indeed, the increase in soil retention near small field reservoirs can be even higher than the retention increase in the reservoir itself. Small water reservoirs contribute to the rise of groundwater in the neighbouring area and increase soil moisture, and this subsequently decreases soil erosion. In studies carried out in the vicinity of the Research Centre for Agricultural and Forest Environment Field Station in Wielkopolska during the spring, small water reservoirs increased water storage by 20 mm (20 l/ m^2 of watershed). With respect to water cycling, many small water reservoirs can increase the intensity of evaporation better than one big reservoir of the same area. For example, evaporation from 100 water reservoirs, each with an area of 0.4 ha under Wielkopolska's climatic conditions, is 30% higher than that from a single large reservoir of 40 ha (Ryszkowski and Kędziora, 1996). Such an evaporative increase from a small reservoir seems, at first glance, to be a water loss. One should remember, however, that high evaporation levels increase the vapour content of the air, which subsequently improves the chances of local condensation (dew) and rain, in terms of both occurrence and intensity. This is particularly true during Wielkopolska's summers.

Drivers of Water Cycling

An important breakthrough in the study of water cycling in landscape ecology has been the use of the energy approach to water flux estimation for large areas. This has involved the development of methods that allow the heat balance of ecosystems (the partitioning of solar energy for evapotranspiration, air and soil heating) to be estimated. This advance has opened up new possibilities for estimating real evapotranspiration rates under field conditions, which, together with information on precipitation and runoff, has enabled the impact of various plant cover structures on water cycling to be evaluated.

The conversion of solar energy for driving natural processes is the fundamental process that ensures that natural systems – including ecosystems or landscapes – can function. The influx of solar energy undergoes partitioning into fluxes driving evapotranspiration. This ensures that water is cycled and that the air is heated (sensible heat flux), determines local temperatures as well as air mass transfer, and heats soils and water. An additional key process that should be borne in mind is photosynthesis, although less than 1% of solar energy is involved in this process. Photosynthesis enables plant biomass production, in which energy is stored and used for all biological processes.

The partitioning of solar energy forms the heat balance of the system, showing the relationships between various energy fluxes. The heat balance equation neglects the biological flux and is usually written in the form:

$$Rn = LE + S + G$$

where Rn is net radiation, LE is latent heat used in evapotranspiration, S denotes the sensible air heat flux and G the subsurface heat flux.

Over a timescale of several years, when changes to plant cover retention can be neglected, the equation for water balance is:

$$P = E + H \pm \Delta R_s \pm \Delta R_g$$

where P is precipitation, E is evapotranspiration, H is surface and underground runoff, ΔR_s is the change in surface water retention and ΔR_g is the change in soil water retention. The retention characteristics can assume positive or negative values depending on water storage change.

For the management of water resources, the coupling of latent heat and evapotranspiration plays a crucial role. Any change in latent heat contribution to the heat balance will bring changes to the water balance. If one can change the heat balance of an ecosystem or watershed then one can influence water cycling. By inducing structural changes in the plant cover of a watershed, it is possible to change the heat balance and therefore also the water balance.

Studies carried out by Ryszkowski and Kędziora (1987, 1995), Kędziora *et al.* (1989), Olejnik and Kędziora (1991), Kędziora and Olejnik (1996, 2002) and Olejnik *et al.* (2002) have led to the development of a model that estimates the characteristics of the heat balance for a large area on the basis of meteorological characteristics and the parameterization of plant cover structure. The model estimates were validated with direct energy flux estimations, using the mean profile method for contrasting ecosystems in the agricultural landscape. Using the latent heat flux to calculate real evapotranspiration, runoff can then be calculated as the difference between precipitation and evapotranspiration, provided the study period is sufficiently long. Runoff calculations for shorter periods additionally require measurements of soil water retention.

This method was used to study the heat and water balance of various ecosystems in Wielkopolska's agricultural landscape, as well as in other countries (Kędziora and Olejnik, 2002; Olejnik *et al.*, 2002). One important finding was that plants increase water transport to the atmosphere owing to evapotranspiration, in contrast to evaporation from bare soil. The comparisons of bare soil and wheat fields during plant growth seasons under semi-desert conditions (Kazakhstan), arid-zone conditions (Spain), steppe-zone conditions (Russia), transit climate conditions in Poland and Germany, and humid-zone conditions (France) showed that plants increased evapotranspiration rates during plant growth seasons by 189% in the semi-desert and by 42% in the humid zone, with values of 54–61% in transit zones (Kędziora and Olejnik, 2002). Much higher increases in evapotranspiration rates were observed in shelterbelts (mid-field rows of trees) or forest patches in comparison with bare soil (Ryszkowski and Kędziora 1987, 1995; Kędziora and Olejnik 2002). It was also shown that the structure of plant cover had an important bearing on the partitioning of solar radiation into other energy fluxes (Table 11.1).

Thus, for example, the energy values used for evapotranspiration (LE) during the plant growth season range from 866 MJ/m^2 (bare soil) to 1522 MJ/m^2 (shelterbelt). The shelterbelt uses nearly 5.5 times less energy for heating air (S) than does bare soil. Energy used for heating soil (G) is the smallest part of net radiation and ranges from 29 MJ/m^2 in meadow to 87 MJ/m^2 in shelterbelt. The shelterbelt uses about 40% more energy for evapotranspiration than the wheat field, while the wheat field diverts approximately three times more energy to heating air than the shelterbelt (Table 11.1). Thus, from the point of view of energy, cultivated fields could be understood as 'heaters' or 'ovens' in a landscape, and shelterbelts or forests can be understood as landscape 'water pumps'.

Table 11.1. Heat balance structure (MJ/m^2) and evapotranspiration (mm) during the plant-growing season (20 March to 31 October) in Turew, Poland, the agricultural landscape (adapted from Ryszkowski and Kędziora, 1987).

	Landscape elements					
Parameter[a]	Shelterbelt	Meadow	Rapeseed field	Beet field	Wheat field	Bare soil
Rn	1730	1494	1551	1536	1536	1575
LE	1522	1250	1163	1136	1090	866
S	121	215	327	339	385	651
G	87	29	61	61	61	47
LE:Rn	0.88	0.84	0.75	0.74	0.71	0.55
E	609	500	465	454	436	346

[a] Rn = net radiation (incoming solar radiation minus outgoing radiation); LE = energy used for evapotranspiration (latent heat flux); S = energy used for air heating (sensible flux); G = energy used for soil heating (soil heat flux); E = evapotranspiration in mm.

Comparing water balances in two contrasting terrestrial ecosystems of a watershed, namely forest and cultivated field under normal climatic conditions, Kędziora and Olejnik (2002) found substantial differences in surface runoff (10 mm in forest and 140 mm in cultivated field) and evaporation (540 and 420 mm, respectively). Despite the fact that the infiltration is 470 mm in forest and 400 mm in cultivated field, the input to subsurface groundwater was only 10 mm higher in forest than in cultivated field (Fig. 11.2). The reason for this offset phenomenon is that the rate of water uptake by trees is more intensive than that of cultivated plants (wheat), which have less developed root systems and therefore have lower access to soil moisture. Thus, the water-pumping effect is clearly seen in forests because of higher evapotranspiration and a higher uptake of soil water.

Precipitation and different runoff rates in basic landscape ecosystems are summarized in Table 11.2. In dry and normal years, similar runoff is observed from forests and grassland landscapes. With abundant precipitation, trees can better control runoff than grasses. The fast and intensive runoff in spring or after heavy rain events leads to a rapid discharge of water from cultivated fields. The uptake of slowly percolating water through the soil by trees and intensive evapotranspiration stop runoff from forests and grasslands in dry years.

Table 11.2. Precipitation and rate of runoff (mm/year) in different ecosystems (modified after Werner *et al.*, 1997).

	Dry year	Normal year	Wet year
Precipitation	627	749	936
Cultivated fields	108	233	351
Grasslands	0	155	271
Forests	0	149	181

The rapid discharge of water is clearly observed in cultivated-field landscapes of Wielkopolska. By the end of spring, ditches draining cultivated fields are dry. In contrast, water can still be observed in forest ditches, even in the late summer. Thus, grasslands and especially forests slow down the discharge of percolating water and store water longer, even under conditions where the input of infiltrating water into subsurface reservoirs is only slightly higher than from cultivated fields (Fig. 11.2).

In a landscape composed of cultivated fields and shelterbelts (Fig. 11.3) one can observe two opposite tendencies in water cycling (Ryszkowski and Kędziora, 1995). Trees increase evapotranspiration rates. At the same time, the protecting effects of trees stimulate decreases in wind speed and lower the saturation vapour pressure deficits, decreasing evapotranspiration. It is for this reason that fields between shelterbelts conserve moisture (Ryszkowski and Karg, 1976; Ryszkowski and Kędziora, 1995). Water conservation can be detected in fields between shelterbelts under all meteorological conditions. The shelter effect is

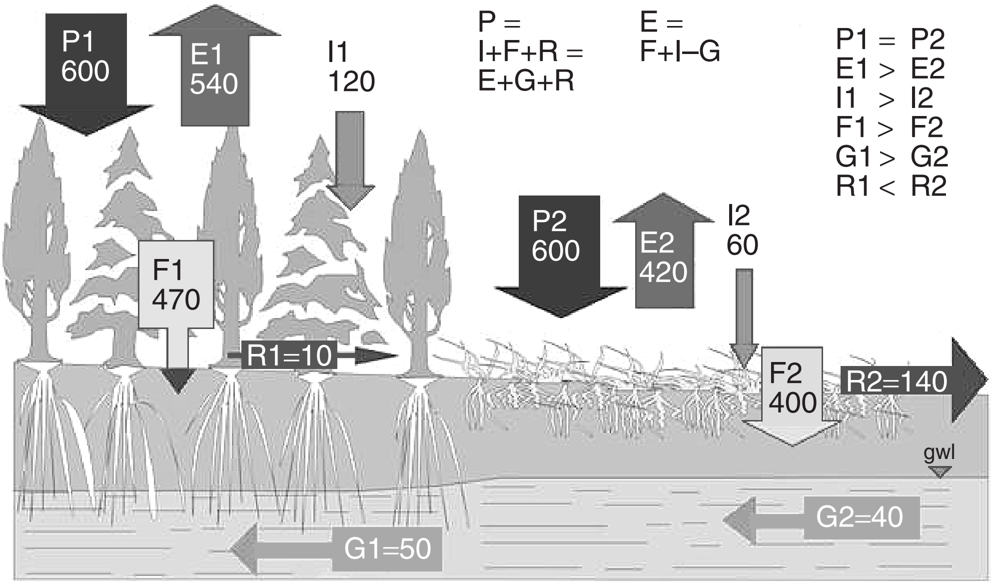

Fig. 11.2. Water balance components of forest (1) and crop field (2). P – precipitation, E – evapotranspiration, I – interception, F – infiltration, R – surface runoff, G – subsurface flow.

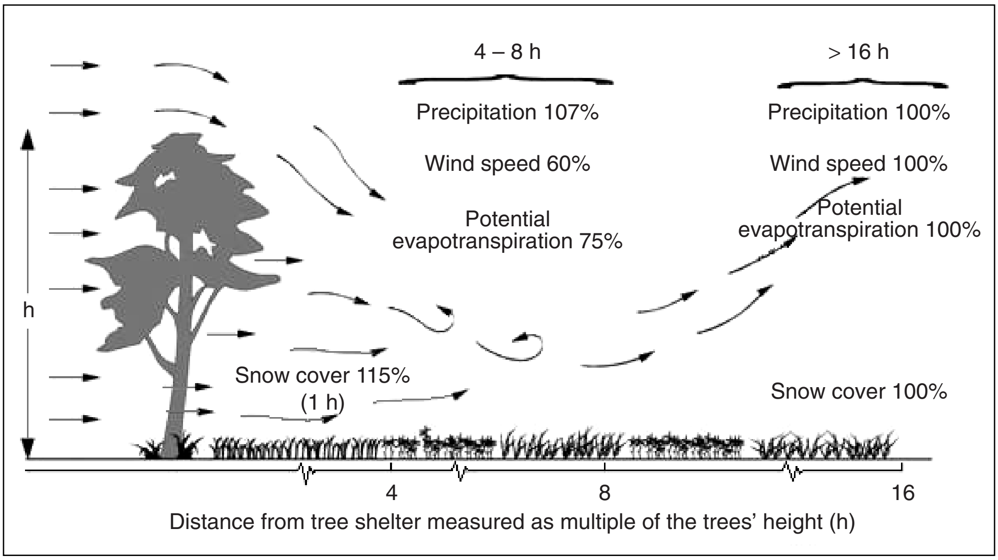

Fig. 11.3. Impact of shelterbelts on microclimate of adjoining fields and evapotranspiration.

greater in dry and warm meteorological conditions than in wet and cool weather. In landscapes with 20% of their area under deciduous shelterbelts, the water saving in sheltered fields amounts to 16 mm under dry and warm conditions. Under wet and cool conditions, 8 mm was saved. But the whole landscape with shelterbelts evapotranspirated 14 mm more than open-field landscapes in dry and warm conditions and 10 mm more when prevailing conditions were wet and cool (Ryszkowski and Kędziora, 1995).

Water Recycling and Storage at the Landscape Level

The horizontal transfer of energy between ecosystems can provide supplies of energy above the level determined by the absorption of direct solar radiation inputs. Thus, for example, the amount of available heat energy for evapotranspiration can be increased in one ecosystem due to its advection from another. Because the heat conductivity of air is very low, the main method of heat transportation is convection, i.e. air movement. The horizontal transport of heat with wind ('heat advection') transfers energy from warmer to cooler places. The structure of a landscape has an important bearing on heat advection processes. As was pointed out above, cultivated fields convert a larger proportion of solar energy into heat than do forests or shelterbelts. Thus, local advection processes frequently originate between non-irrigated cultivated fields and adjoining shelterbelts.

The illustrative example of an important impact of heat advection on water balance structure is the case of very strong advection observed near Zaragoza, Spain in July 1994. Dry areas surrounded irrigated, well-developed fields of lucerne. During windless and sunny days, average net radiation (Rn) varied from 170 to 180 W/m^2 and nearly all was used for evapotranspiration, and the ratio of latent heat (LE) to net radiation amounted to about one. The daily evapotranspiration rate reached as much as 7.4 mm. But, after a few such days, a cloudy and windy day followed. Even though the net radiation dropped to 65 W/m^2, the air temperature increased by 1 °C and strong evapotranspiration caused the cooling of the lucerne surface, resulting in strong advection. The flux of heat transported by the air motion from the dry areas reached as much as 48 W/m^2 and was totally used for evapotranspiration. Even the soil heat flux changed direction and brought about 16 W/m^2 to the evaporating lucerne surface. All these processes of energy exchange were caused by the evapotranspiration and water availability owing to irrigation. As a result of these additional inputs of energy, evapotranspiration remained intensive, with a value of 4.6 mm/day, and the LE/Rn ratio reached the extremely high value of two. In other words, the energy used for evapotranspiration exceeded net radiation (Rn) by 100%. So, although net radiation was threefold lower than on the previous sunny day, evapotranspiration, thanks to the advection effect, dropped by only a third (Kędziora *et al.*, 1997).

The substantial influence of the heat advection processes on subsurface water fluxes was demonstrated in the following estimation. Net radiation was directly measured, and its value during the plant-growing season in sunny days (relative sunshine above 0.6) ranged from 80 to 150 W/m^2 for 24 h. For the model to estimate evapotranspiration, the value of 100 W/m^2 was taken for an average sunny day, while the value for an average cloudy day (relative sunshine below 0.3) was taken to be 50 W/m^2. The hydraulic conductivity of soil was 5 m/day, effective porosity 0.2 m^3/m^3 and the depth of the filtrating layer 4 m. Finally, the runoff for a normal year was 100.7 mm. Other parameters needed for calculations were also measured (Ryszkowski and Kędziora, 1993). It was found that when additional energy was provided from cultivated fields by advection, evapotranspiration increased, and water flux under a 10 m-wide shelterbelt was reduced by 56% when the slope steepness was 0.04. Under the same conditions, the ground water flux under a strip of meadow was reduced by a factor of 0.36. On cloudy days, with advection on slopes with 0.04 steepness, evapotranspiration in the shelterbelt reduced the ground water flux by 0.24 and in meadows by 0.19. If the steepness of slope is lower (0.01), on sunny days almost all seeping water is taken up for evapotranspiration. Thus, slope steepness and energy input determine the passage of water under shelterbelts and strips of meadow. The other important conclusion is that the larger the influx of energy, the more important are the differences in plant cover structure (tall trees or short grasses) for the control of the groundwater flow beneath them.

Plants, like trees and lucerne with deep root systems, can use water not only stored in the aeration zone of the soil but also from saturated zone (shallow groundwater). A model for the estimation of plant water uptake from the unsaturated soil zone and shallow groundwater was developed (Kayser, 2003, unpublished thesis). The uptake of groundwater is an important process, diverting or capturing water from the flux out of a watershed to a drainage system. This is one intra-landscape mechanism of water recycling. The ratio of groundwater uptake to actual evapotranspiration shows the intensity of withdrawal of outflowing water for ecosystem uses. This ratio (p) depends on actual evapotranspiration (ETR in mm) and groundwater depth (GWL in m). The following equation describes this relationship for shelterbelts in Wielkopolska, Poland:

$$P = 0.56 - 0.49 \cdot \exp [0.29 \cdot (ETR:GWL)]$$

The mean ETR value is calculated for a half-month period and GWL is the average value for the same timespan.

It was found that the proportion of water taken up from the groundwater aquifer for shelterbelt evapotranspiration is greater in warmer weather and in cases of shallow water level (Fig. 11.4). The estimates of groundwater average share in evapotranspiration during the plant growth season varied from 0.244 during cold weather and a deep groundwater level (1.5 m depth) to 0.439 in warm weather and a shallow groundwater table (0.5–1.0 m depth). At the beginning of the plant growth season in a cold-weather year, groundwater was the source for only 18% of actual evapotranspiration by the shelterbelt, but in a warm-weather year 37% of actual evapotranspiration was from groundwater (Fig. 11.5). It seems that, when there is enough moisture in the spring, trees mainly use water from the unsaturated soil zone. When temperatures and evapotranspiration increase, and water supplies in the upper part of the soil decrease, trees use more and more water from ground aquifers. In June, the ratio of groundwater taken up to evapotranspiration increased to 30% if there was cold weather, and up to 50% during warm weather. One can assume that besides a higher withdrawal of groundwater for evapotranspiration – which denotes a higher rate of recycling – the shelterbelts were probably also more efficient at controlling diffuse pollution in groundwater during summer.

As was shown above, the transfer of heat energy by advection enhances evapotranspiration rates and the uptake of seeping groundwater. The impact of advection is much higher in the case of shelterbelts than in the case of large forest areas because the advection flux did not reach trees inside the forest. The evapotranspiration per mean unit of shelterbelt area is higher, therefore, than per mean unit of area in forest (Fig. 11.6). Such a situation increases the uptake of groundwater by shelterbelts, and so decreases the discharge of water from a watershed into a drainage system. In a watershed intersected by shelterbelts, there is also lower surface runoff because of the mechanical effect of tree strips stimulating water infiltration.

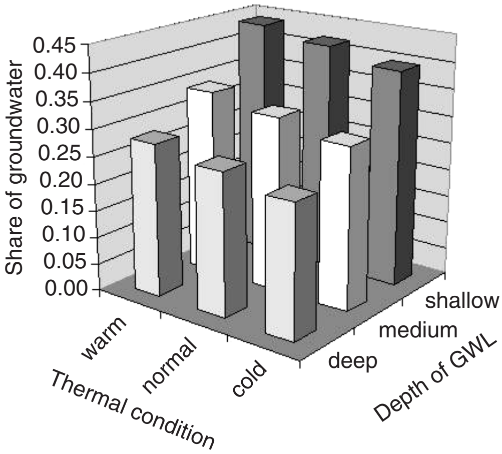

Fig. 11.4. Fraction of water taken up by shelterbelt from the saturation zone under different thermal conditions and different groundwater depths. Groundwater level – deep: 1.5 m in April to 2.5 m in, September, medium: 1.0 m in April to 1.75 m in September, shallow: 0.5 m in April to 1.0 m in September. Temperature conditions – normal: 14.4 °C (average for vegetation season in long-term period), warm: 15.4 °C, cold: 13.4 °C.

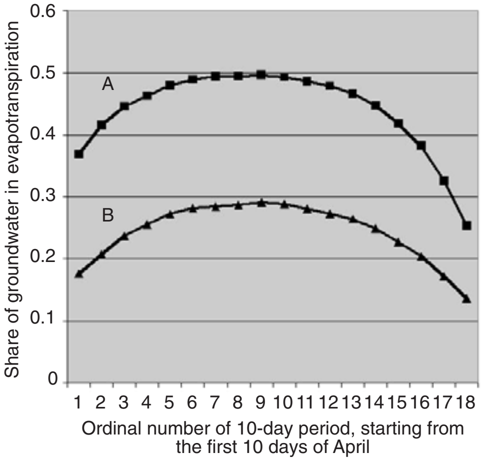

Fig. 11.5. Share of groundwater in evapotranspiration related to weather conditions and depth of groundwater level. A – warm weather and shallow groundwater level; B – cold weather and deep groundwater level. Groundwater level – deep: 1.5 m in April to 2.5 m in September, medium: 1.0 m in April to 1.75 m in September, shallow: 0.5 m in April to 1.0 m in September. Temperature conditions – normal: 14.4 °C (average for vegetation season in long-term period), warm: 15.4 °C, cold: 13.4 °C.

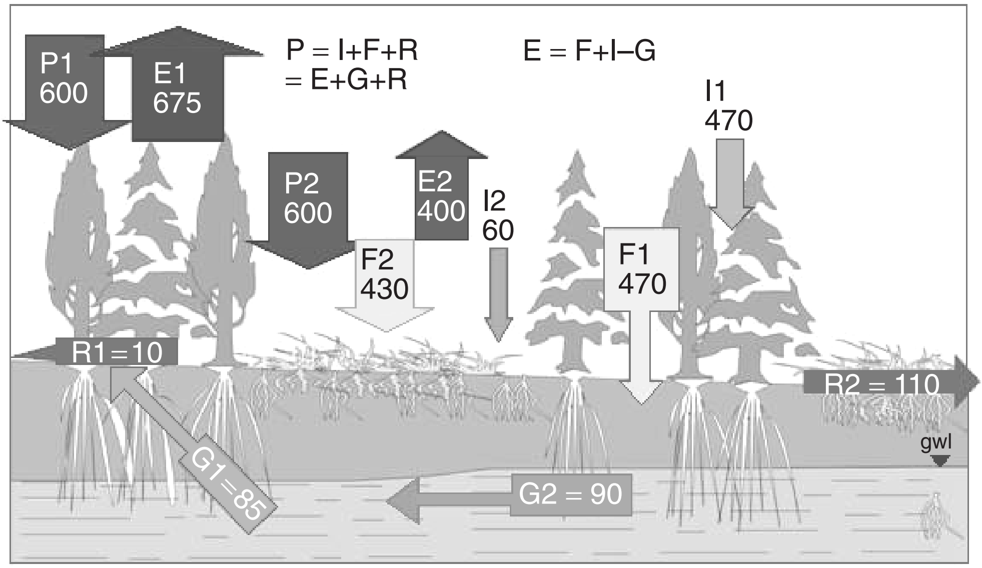

Fig. 11.6. Water balance components of shelterbelts (1) and crop field (2) located between shelterbelts. P – precipitation, E – evapotranspiration, I – interception, F – infiltration, R – surface runoff, G – subsurface flow.

The high evaporation rates of forests have an important bearing on the water regime of a region. Usually, in humid climatic zone landscapes, the water balance is positive – i.e. the water input with precipitation is higher than evaporation. In Poland, evapotranspiration from cultivated fields is higher than precipitation in the plant growth season and water is taken from soil moisture reserves built up in autumn, winter or early spring. The forest as a 'landscape water pump' is characterized by very high rates of evapotranspiration. So, an increase in forest areas brings about lower runoff from the watershed. But water used for evapotranspiration is not a total loss for the region. Intensively evaporating forest increases air moisture and by doing so forms favourable conditions for water condensation and cloud formation, and due to these processes, precipitation can increase (Fig. 11.7). Bac (1968) estimated that, under Polish conditions, a 1% increase in the afforested area would yield a 5 mm increase in precipitation. The relationship between evaporation rates and precipitation intensity can only be observed over large forest areas. Otherwise, the effects of small afforested patches are negligible.

Bearing in mind that cultivated fields are 'landscape ovens', then moist air flowing from intensively evaporating forest over cultivated fields generates cloud as strong uplifting convective heat fluxes from the fields drive it upwards (Fig. 11.7).

The influence of plant cover structure on weather, including the formation of rain clouds, is recognized by climatologists (see Pielke *et al.*, 1998 for a review of the rich literature). A heterogeneity of land cover structure influences energy budgets, which generate mesoscale atmospheric circulations that can focus rainfall (Atkinson, 1981; Cotton and Pielke, 1995). Blyth *et al.* (1994) have shown that if 160,000 km^2 in south-west France were completely covered by forest, frontal rainfall could increase by 30% in comparison with bare soil. Anthes (1984) has hypothesized that, by spacing vegetation in semi-arid regions, cumulus convective rain can be optimized. Thus, the influence of forests on rainfall at the mesoscale is fairly well recognized.

There are also studies that indicate that forest clearing at the bottom of the Monteverde Mountains in Costa Rica decreases precipitation events in adjoining cloud forest on the slopes of the massif. Deforestation and the conversion of land to pasture decreased evapotranspiration and the moisture content in air masses, as well as lifting condensation levels. Therefore, air coming in to the cloud forest from low slopes brings less moisture (Lawton *et al.*, 2001). A similar phenomenon was detected earlier by Stohlgren *et al.* (1998) in the Rocky Mountain National Park (Colorado, USA), where land-use changes in adjoining plains changed cloud-forming processes over mountains.

Water loss through evapotranspiration could be minimized within landscapes if precipitation

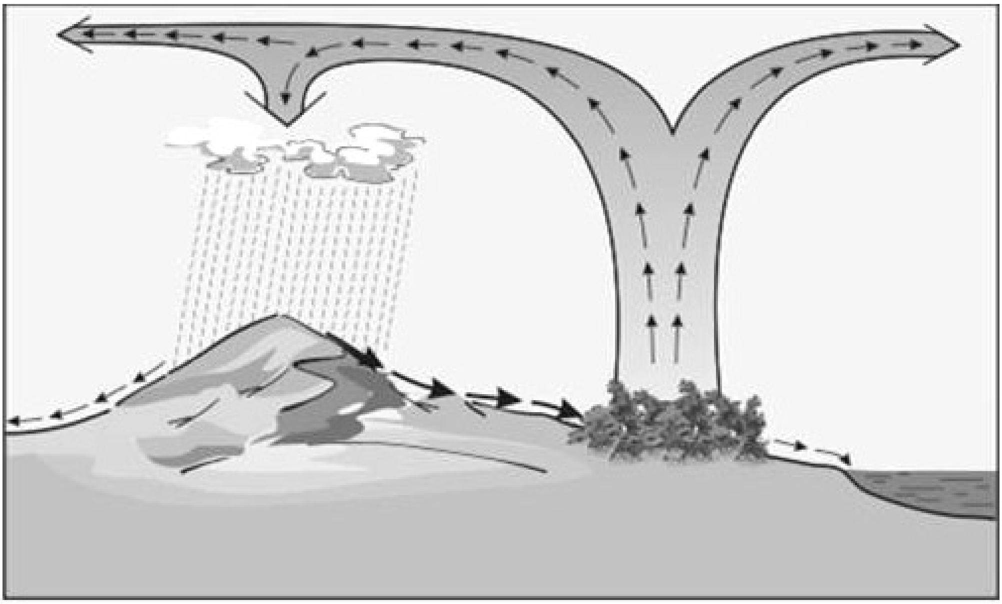

Fig. 11.7. Water evapotranspirated by forest is partly involved in local circulation and partly in global circulation.

occurs close to the evapotranspiration source. The formation of cumulonimbus clouds or storm clouds usually results in water transport over short distances. If air is saturated with water (intensive evapotranspiration) and there is warm air with a weak wind, then moist air masses flowing in over a convective area (cultivated fields) will form storm clouds, and rainfall will occur at a distance of just a few km from the evaporation site. Thus, short-range recycling of water can be brought about by storm clouds. The frequency of this short-range recycling of water among rain events in the Wielkopolska area is about 20% (J. Tamulewicz, personal communication).

Kędziora and Ryszkowski (2001) estimated that, when forests cover 45% of a large area, then inputs of water in precipitation overcome losses in evapotranspiration (Fig. 11.8). This estimate was based on the assumption that an increase in forest area by 1% brings about a 5 mm precipitation increase under normal Wielkopolska climatic conditions (Bac, 1968). If these estimates are accurate, effective water recycling will occur if a large area has 45% forest cover. This point, however, requires further study.

Feedbacks between various meteorological processes have long been recognized (e.g. Thom, 1975). The energy analysis described above allowed the control mechanisms of these processes to be revealed, and enabled a better understanding of the interactions between various processes. The ratio of energy used for evapotranspiration (LE) to net radiation (Rn) (difference between incoming and outgoing radiation) characterizes the energy efficiency of evaporation.

The energy-based indicator of ecosystem wetness (W) can be characterized by the ratio of energy needed for the evaporation of total precipitation (P) to the available energy provided by Rn. The energy required for the evaporation of total precipitation is calculated by the multiplication of rainfall amount (mm or kg/m^2) during the plant growth season by the latent heat of evaporation (L), which is equal to 2.448 MJ/kg. Thus:

$$W = (P \cdot L) : Rn$$

On the basis of studies carried out in Kazakhstan (semi-desert), arid conditions (Zaragoza, Spain), transit zones (Kursk, Russia), Turew (Poland) and Müncheberg (Germany) and in a humid zone (Cessieres, France), the influence of habitat moisture and plant cover, as well as the synergetic impact of these two factors on evapotranspiration, was evaluated (Kędziora and Olejnik, 2002). Estimations of heat balances were done for bare soil and wheat cultivation (with and without irrigation) in each location.

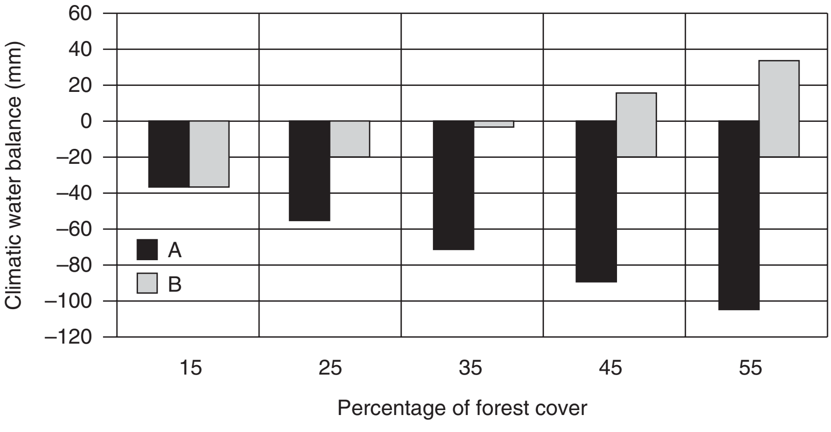

Fig. 11.8. Seasonal climatic water balance (precipitation–evapotranspiration), without feedback between evapotranspiration and precipitation (A) and with feedback (B), assumed, after Bac (1968), that a 1% increase of forest area would increase precipitation by 5 mm.

The three ratios, which characterize the influence of plant cover and irrigation and their synergetic effects, were calculated in the following way:

k1 – impact of plant cover introduction (LE:Rn of cultivated field with normal moisture conditions divided by LE:Rn of bare soil).
k2 – impact of irrigation (LE:Rn of irrigated field divided by LE:Rn of cultivated field with normal moisture conditions).
k3 – synergetic effect of plant cover and irrigation (LE:Rn of irrigated field divided by LE:Rn of bare soil).

The impact of plant cover and irrigation on the effectiveness of energy use for evapotranspiration quickly increases with climate dryness (Fig. 11.9). In addition, the synergetic effect is clearly seen, because the combined effect of plant cover and irrigation is much higher than the sum of these factor influences treated separately. Thus, positive feedback mechanisms are observed between plant cover and irrigation, and should be taken into account when economic evaluation of irrigation is performed. This particularly concerns semi-desert and arid ecosystems.

The Ecological Background for Water Management Strategy in Rural Areas

The modification of the water cycle by plants, until recently, had not been factored into water management strategies. The main emphasis was on making use of technical solutions to manage water resources and enabling the easy economic calculation of their exploitation in agricultural production. The recent progress in landscape ecology shows that evapotranspiration and surface and ground runoff are strongly influenced by changes in plant cover structure. Saving moisture in fields between shelterbelts, water storage

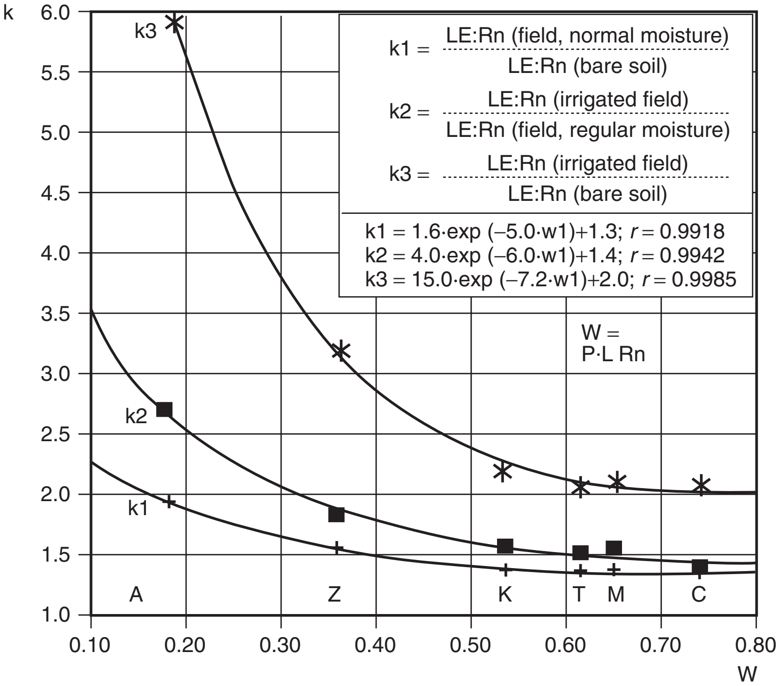

Fig. 11.9. Efficiency of solar energy used for evapotranspiration during the vegetation season as a result of habitat moisture and climatic conditions. Rn – net radiation (MJ/m^2), LE – latent heat flux density of evapotranspiration (MJ/m^2), P – precipitation (mm), L – latent heat of evaporation (2.448 MJ/kg), W – indicator of ecosystem wetness, A – Alma-Ata (Kazakhstan), Z – Zaragoza (Spain), K – Kursk (Russia), T – Turew (Poland), M – Muncheberg (Germany), C – Cessieres (France), k1 – impact of plant cover, k2 – impact of irrigation, k3 – synergetic effect of plant cover and irrigation.

in small mid-field ponds and water recycling within the watershed can increase water retention in the landscape. Kędziora and Olejnik (2002) showed that plant cover within a catchment:

- Increases evapotranspiration.
- Limits surface runoff due to increased infiltration rates to soil and evaporation.
- Slows down water fluxes and increases the time of subsurface runoff discharge from soils.
- Modifies microclimatic conditions (in fields protected against wind by trees; evaporation is lower than in the case of a uniform area of cultivated fields).

Thus, manipulation of the landscape with plant cover can bring important changes in the water flow rate, which has a bearing on the ecosystem functions.

An evaluation of the water balance based on the analysis of water supply and outflow is the foundation for proposals on the efficient control of threats caused by water deficits or excesses in a particular catchment area. It should be stressed once again that the mere use of fragmentary information on the water balance (e.g. the amount of rainfall or the quantity of water intake for municipal or economic purposes) is not sufficient to define guidelines for water management. Only by understanding the all-important ways of water cycling can the foundation of a water management strategy be developed. Thus, for example, relying only on precipitation and evapotranspiration rates for estimating the amount of water accessible to people will neglect the effects of water recycling, which, according to some estimates, can increase available water resources by 30% (Blyth *et al.*, 1994). Greater study of water recycling in watersheds is required before the magnitude of this phenomenon in various ecosystems is fully understood. Nevertheless, the importance of horizontal energy fluxes between various ecosystems due to differences in the structure of heat balances of adjoining ecosystems brought about by human activity has recently been recognized. One of the interesting results from the above studies on heat balances in landscapes concerns the importance of heat transport processes between nearby ecosystems by advection transfer. Heat advection processes can modify evapotranspiration rates by as much as 40%.

Owing to progress in ecosystem studies, an understanding has emerged that water should be shared between people and ecosystems in order to maintain ecosystem services. Thus, a new challenge has emerged for scientists and decision makers to elaborate methods for the evaluation of water quotas that can be used by people and do not undermine ecosystem services.

The other important principle of ecological water management is the necessity to refer it to the catchment, in which the optimization of different interactions between landscape structures can be achieved for the most economical exploitation of available water resources. The modification of microclimatic conditions using vegetation, for example by the use of shelterbelts, along with the relocation of water resources, with the help of drainage-ditch networks or drain pipes to field ponds or temporarily flooding ground depressions to store water, can effectively slow down runoff and flatten flood waves over large areas. The positive effects of increased evapotranspiration on precipitation are appreciable only over large areas. Therefore the effective management of water resources requires activities and incentives at the scale of two different systems of management, namely within the farm and within a catchment or landscape.

Recent developments in landscape ecology increase recognition of the natural processes operating in an agricultural landscape. These results facilitate the invention of alternative technologies under objectives which seek to optimize agricultural production, environmental protection and meet social needs at the same time. From the results of investigation into landscape functioning, one may conclude that a purposeful structuring of catchment areas will expand the arsenal of water-protective means and provide more economical ways of water use. Those new technologies of landscape management should be incorporated in the implementation of sustainable agriculture programmes.

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