The interaction between water and energy of greened roofs

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Abstract

Worldwide, energy consumption for cooling and ventilation installations is becoming increasingly important. With the new directive of the European parliament on the energy performance of buildings (2002/91/EC), passive cooling techniques should be implemented that improve indoor climatic conditions and the microclimate around buildings. The rise of air conditioning systems, in particular, forces energy conservation strategies on the building sector. Impermeable surfaces like roofs and streets influence the microclimate by creating a different energy balance from that which is found in green spaces. Natural landscapes, like meadows, evaporate most of the precipitation that they receive. This physical process generates “evaporative cooling,” worth 2450 Joule/g H2O. This consumes 86% of all radiation balance as a yearly average. This energy is used to transpire water and create biomass. The evapotranspiration of greened roofs and greened facades has a high potential to reduce the urban heat island effect. According to measurements taken at the UFA Fabrik in Berlin, during the summer months extensive green roofs transfer 58% of the radiation balance into transpiration. As an annual mean, 81% may be consumed. The resultant cooling-rates are on average 300 kWh/ (m^2*a) in Germany. In tropical countries, much higher cooling values may be expected, due to higher precipitation and evapotranspiration rates. The annual retention rates, due to the evapotranspiration of precipitation, are independent of a second important value: the temporary retention of stormwater. This successfully reduces the peak load into combined sewer systems and prevents combined sewage release into surface waters.

Die Wechselwirkung zwischen Wasser und Energie von begrünten Dächern

Der Energieverbrauch für die Gebäudekühlung ist weltweit von wachsender Bedeutung. Die neue Richtlinie des europäischen Parlaments über die Gesamtenergieeffizienz von Gebäuden (2002/91/EC), die bis zum Januar 2006 von den Mitgliedsstaaten in nationales Recht umgesetzt werden muss, sieht die Berücksichtigung von Maßnahmen zur passiven Gebäudekühlung vor. Insbesondere die rasant steigende Verwendung von Klimaanlagen zwingt zu neuen Strategien bei den Energiesparmassnahmen im Gebäudebereich. Versiegelte Flächen wie Dächer und Strassen haben ein unterschiedliches Mikroklima durch die Veränderung der Energiebilanz, verglichen mit begrünten Flächen. Der größte Teil der Niederschläge in der „natürlichen“ Landschaft wie beispielsweise Wiesenflächen verdunstet. Dieser physikalische Prozess erzeugt eine Verdunstungskälte von 2450 Joule pro Gramm Wasser. Hierbei wird mehr als 85% der jährlichen Strahlungsbilanz „verbraucht“. Diese Energie wird bei der Evapotranspiration und den Aufbau von Biomasse umgesetzt. Die Verdunstung von begrünten Dächern und begrünten Fassaden zeigt ein hohes Potenzial, den Effekt der Wärmeinsel urbaner Gebiete zu verringern. Messungen, die wir auf den Dächern der UFA-Fabrik in Berlin-Tempelhof durchgeführt haben, zeigen, das extensiv begrünte Dächer 58% der Stahlungsbilanz in Verdunstungskälte während der Sommermonate verwandeln. Als Jahresmittel können 81% der Strahlungsbilanz „verbraucht“ werden, dies entspricht einer Kühlung von 300 kWh pro Quadratmeter und Jahr in Deutschland. In tropischen Ländern sind höhere Werte zu erwarten durch hohe Niederschlags- und Verdunstungsraten. Der jährliche Rückhalt der Niederschläge durch Verdunstung ist unabhängig zu einem zweiten wichtigen Faktor: dem Abflussbeiwert bei Starkregen. Dieser teilweise temporäre Rückhalt reduziert den Spitzenabfluss in Mischkanalisationsgebieten und trägt so zur Verringerung von Mischüberläufen in die Oberflächengewässer bei.

1 Methodology of Research

The first measurements detailing the climatological effect of greened roofs and facades were established in Berlin Kreuzberg by Friedrich Bartfelder and Manfred Köhler in 1984. These first measures of sustainable city renewal were developed by the group “Ökotop”. In 1986, Köhler started measuring ecological conditions on about 100 greened roof plots of 2 m². The change in climatological conditions were hardly understood by measurements of temperatures in and on top of the soil. Main difficulties have been the high exchange rates of the air, the heat capacity of the materials and the influence of the surface color, the albedo (Schmidt 1992).

To understand the ecological functions of greened areas compared to sealed urban areas our focus moved towards radiation and the evapotranspiration rates. Environmental changes in urban areas include reduced evapotranspiration of the precipitation, the transformation of the radiation to latent heat and the increase of thermal radiation caused by higher surface temperatures and increased heat capacity.

2 Annual retention by evapotranspiration and the change in microclimate

The energy consumption for cooling and ventilation units in buildings is a factor of growing importance. The rising costs for air conditioning has been a factor to promote energy saving efforts in the building sector. The new directive of the European parliament on the energy performance of buildings (2002/91/EC) requires the implementation of passive cooling techniques that improve indoor climatic conditions and the microclimate around buildings. The new legislation has to be set into national law until January 2006.

Passive cooling techniques can reduce or save operating costs for climate managment through the greening of roofs and facades. The main factor differentiating greened areas in the natural landscape from the impermeable surfaces of urban areas is the change of microclimate, which creates a different energy balance. Compared to urban areas where rainwater disappears into sewer systems, most of the precipitation in the natural landscapes is evaporated. For example, in natural landscapes in the Spree and Havel watershed of Germany, approximately 80% of the precipitation is evaporated or transpired by plants (see Fig. 1 “meadow”). Energy is required for the evapotranspiration of water. This physical process generates the so-called “evaporative-cooling” of 2450 joules/g H_2O evaporated. A cubic meter of water has the capacity to consume 680 kWh of heat.

According to research from Hamburg, Germany in 1957, greened areas like meadows consume a yearly average of 86% of all radiation balance (Collmann, 1958). This energy is used to transpire water and create biomass. The consumed energy will be transformed again as water condenses in the atmosphere.

Annual evapotranspiration rates of greened roofs means the evapotranspiration of precipitation. This precipitation/ runoff-ratio depends on the local climate, the vegetation and the green roof type, mainly the field capacity of the soil (storage capacity for rainwater). Fig. 1 shows the mean annual evapotranspiration rates of different surfaces, three of which are different green roof types. These values have been measured at research installations of our institute in Berlin-Wilmersdorf. A meadow on a loamy soil shows evapotranspiration rates of 87 and 89%, depending on the groundwater level. In addition, Fig. 1 shows the surface runoff, evapotranspiration and groundwater recharge of semi-permeable surfaces. Generally, semi-permeable surfaces permit more groundwater recharge compared to the natural landscape.

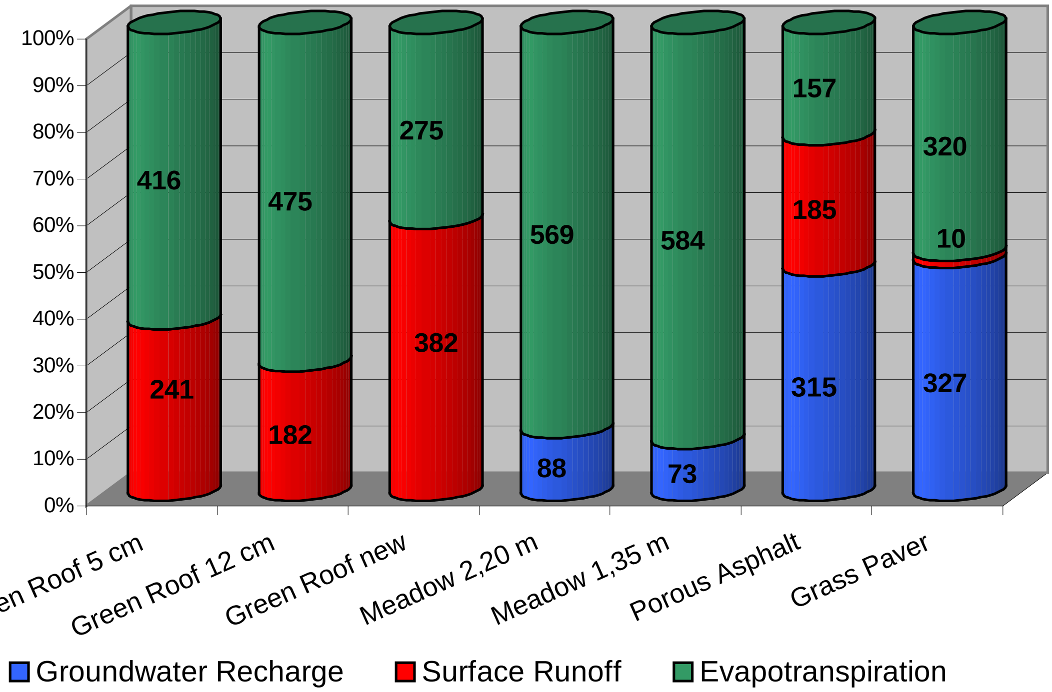

Fig. 1 Hydrology of different surfaces (in mm), 1.1.2001-31.12.2004 TU Berlin

Environmental changes in urban areas include reduced evapotranspiration of the precipitation and the transformation of up to 95% of the radiation balance to latent heat (Fig. 3). Additionally, there is an increase in thermal radiation caused by higher surface temperatures of hard materials like concrete and the ability of such surfaces to store heat (Fig. 2) (Köhler, Schmidt, 2002).

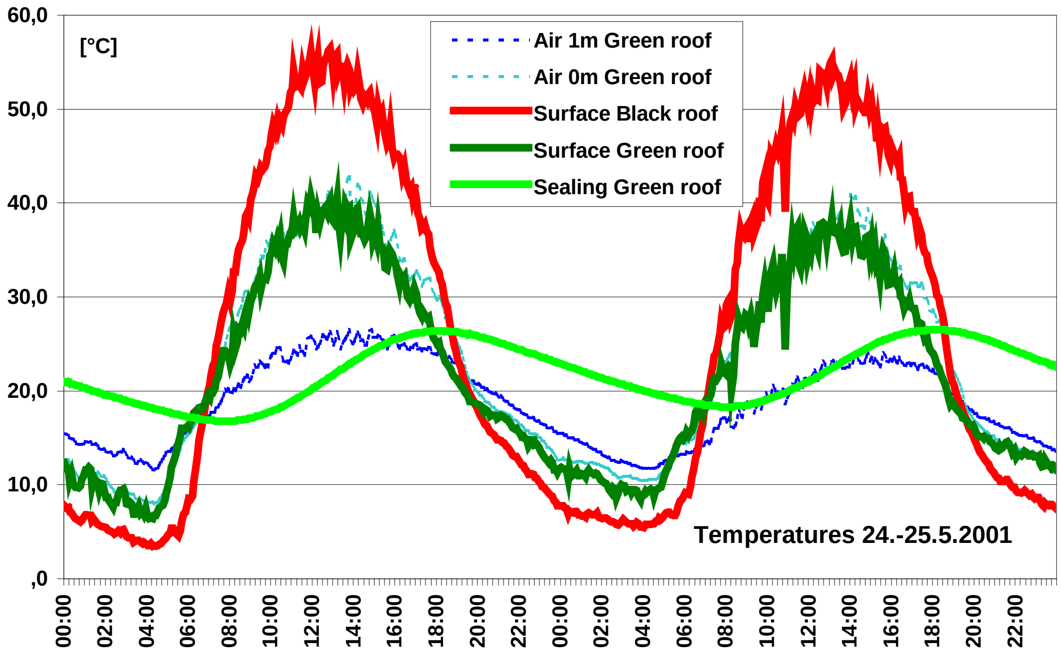

Fig. 2 Reduced surface temperatures of a greened roof compared to a conventional flat roof (non-contact infrared measurements)

As a result, air temperatures inside buildings also rise and lead to discomfort or increased energy consumption for climate management. A logical solution to create more comfortable air temperatures inside and outside of buildings is to green their facades and roofs, thereby „consuming“ this energy by evapotranspiration.

According to measurements taken at the UFA Fabrik in Berlin, extensive green roofs transfer 58% of radiation balance into evapotranspiration during the summer months (Fig. 4). The annual average consumption of energy is 81%, the resultant cooling-rates are 302 kWh/(m²*a) by a radiation balance of 372 kWh/(m²*a) (average of 1987-89, see Tab. 1). In tropical countries, much higher cooling values are expected due to higher precipitation and evapotranspiration rates. In these countries energy saving strategies should focus on passive cooling techniques.

Photo 1 Extensive greened roof in combination with photovoltaic panels, UFA-Fabrik in Berlin-Tempelhof

Tab. 1 Precipitation, runoff, potential and measured evapotranspiration, and the evaporation cooling rate of green roof plots, measured in Berlin (Schmidt, 1992)

Year	**Precipitation**	**Runoff**	**Runoff**	**potential ETP**	**measured ETP**	**Cooling rate**
	[mm]	[mm]	[%]	[mm]	[mm]	[kWh/(m²*a)]
1987	702	179	25.5	641	523	356
1988	595	157	26.4	696	437	298
1989	468	98	20.9	750	370	252
mean	**588**	**145**	**24.6**	**696**	**443**	**302**

Energy balance of a greened roof compared with a black bitumen roof

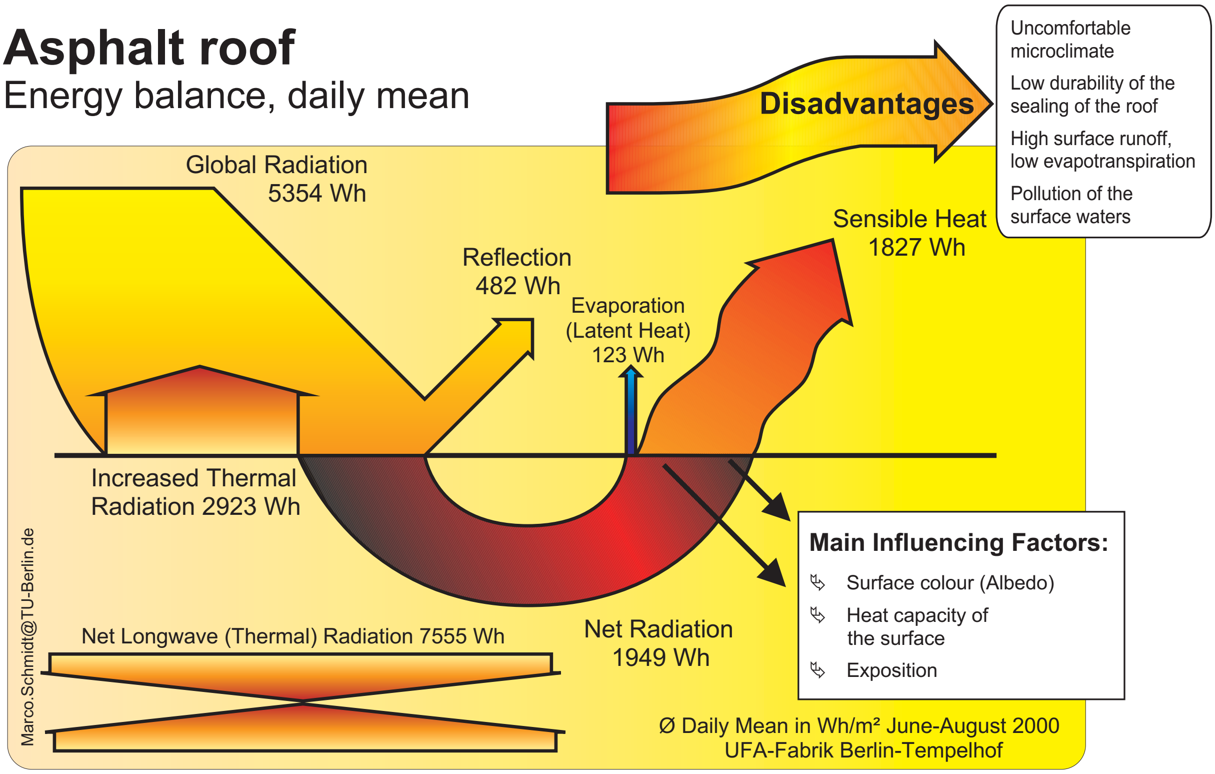

Fig. 3 Reduced evapotranspiration in urban areas converts up to 95% of net radiation to sensible heat and increases the thermal radiation

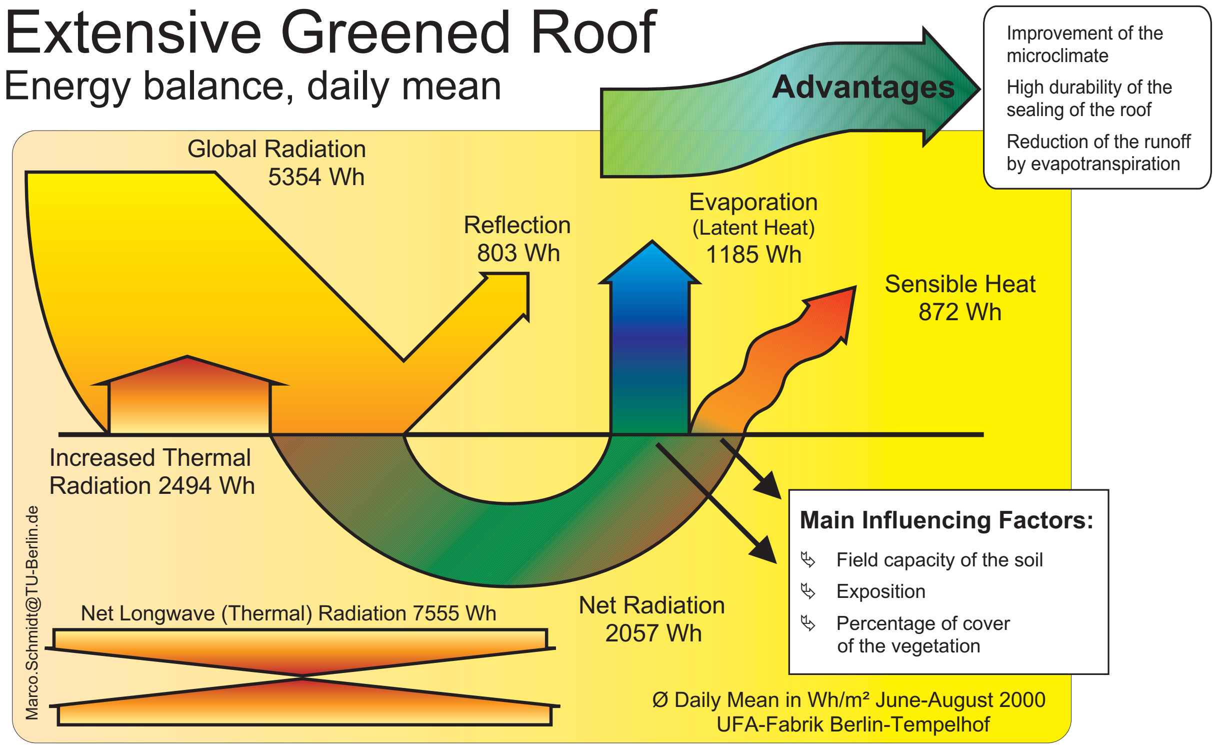

Fig. 4 Extensive greened roofs transfer 58% of net radiation into evapotranspiration during the summer months, UFA Fabrik in Berlin, Germany

3 Stormwater retention

Another important aspect of greened roofs is their capacity for stormwater retention. This capacity successfully reduces combined sewerage overloads (Knoll, 2000) (see Fig. 5). The temporary retention rate of stormwater runoff is an independent value and should not be confused with the annual retention rates for evapotranspiration.
Combined sewage overflows are a serious health problem. The eutrophication of surface waters will occur, combined with reduction of oxygen. In July 2005 in Berlin, reduced oxygen in the Spree river caused tons of dead fish after a heavy stormwater event (see Photo 2).

Photo 2 Tons of dead fish after a heavy stormwater event (www.planungsfehler.com)

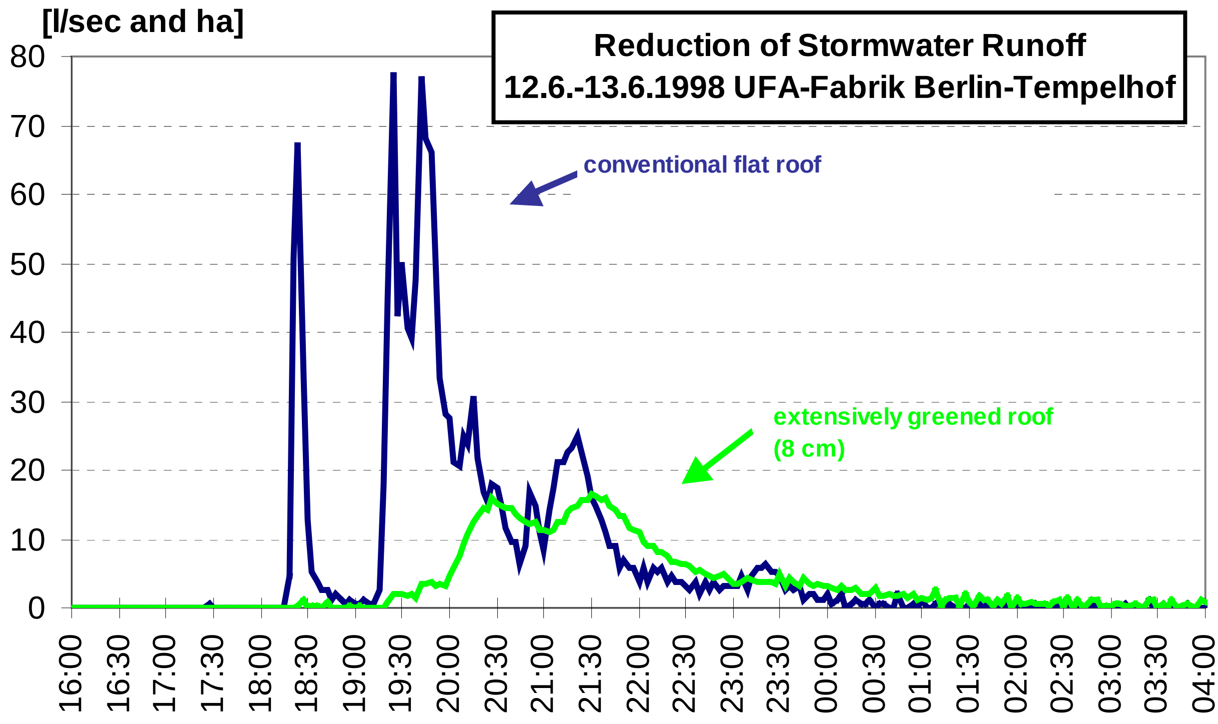

Fig. 5 Reduction of stormwater runoff, an extensively greened roof compared to a conventional flat roof.

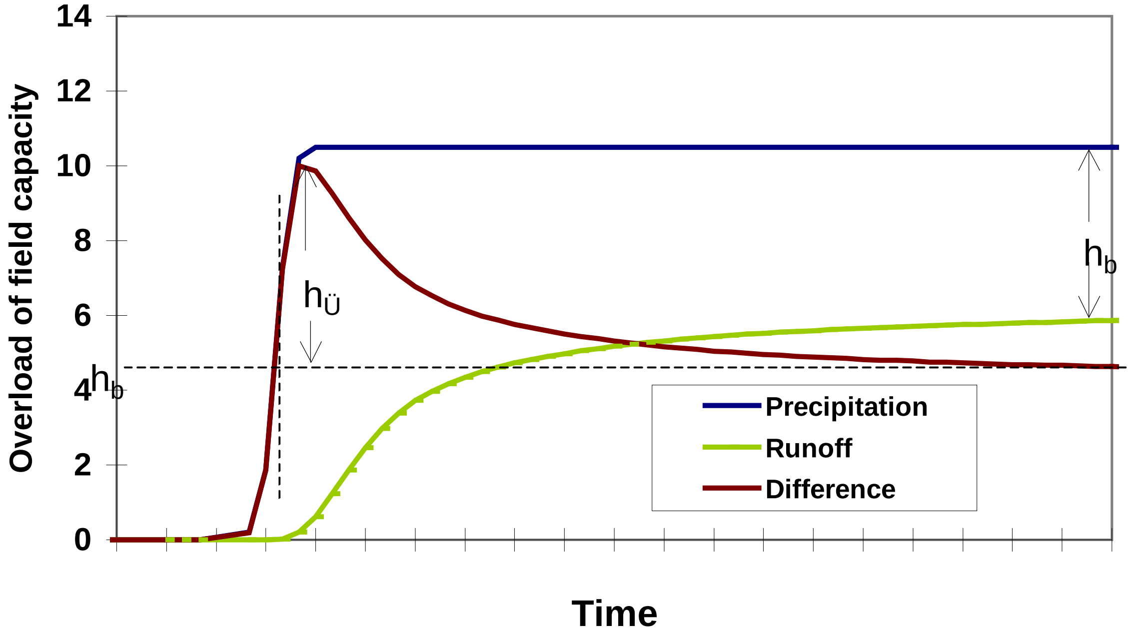

Fig. 6 Reduction of stormwater runoff, an extensively greened roof compared to a conventional flat roof (Bustorf, 1999).

Compared to annual retention rates by evapotranspiration, stormwater retention shows results of up to 90 and 100%. Stormwater retention means an additional temporary storage capacity over the field capacity of the soil. Figure 6 shows the overload of a greened roof during a stormwater in May 1997, expressed in millimeter of rainfall as a difference between precipitation and runoff (Bustorf, 1999). The overload showed a capacity of more than 10 mm of precipitation. A second important aspect is the time delay of the runoff. Figure 5 shows that runoff starts when the peak of the stormwater has already ended. This is a high benefit for sewer systems.

4 Institute of Physics in Berlin- Adlershof

The Institute of Physics in Berlin- Adlershof, a project of the Architects Augustin and Frank (Berlin), is a research and office building that will feature a combination of sustainable water management techniques, including the use of rainwater to cool the building. There are three main goals of rainwater harvesting in this project. The first goal is to save drinking water. The second is the retention of rainwater to reduce stormwater flows into combined sewer systems during rain events. This reduces the peak load and avoids an overload of the system, which could cause flooding and serious health problems. The third goal is to reduce energy consumption during the summer months through evapotranspiration and shade (Schmidt, 2003).

Photo 3 Climbing plants at the institute of Physics in Berlin provide shade and cooling by evapotranspiration

Rainwater will be stored in 5 cisterns in two courtyards of the building and will be used for irrigating a facade greening system and an adiabatic cooling system. The green facade with its different types of climbing plants has been designed to demonstrate the four seasons. The plants will provide shade during the summer, while in the winter, when the plants loose their foliage, the sun's radiation will pass through the glass front of the building. This project will include ongoing monitoring of water consumption by different plant species comprising the green facade and the adiabatic cooling system. Both the shade created by the plants and the cooling process of evapotranspiration will influence the energy balance of the building.

Tab. 2 Project data of the new building of the Humboldt-University in Berlin (HUB)

Connected Area	**Institute of Physics Berlin HUB - Adlershof**	
	Air conditioning systems with adiabatic cooling:	7 units
	Irrigated Greened Containers:	152 plots
	Connected roofs:	4700 m²
	Pond in the courtyard:	225 m²

Stormwater events with heavy rainfall will be managed by the overflow to a small constructed lake in one of the courtyards. The institute is located in a groundwater protection area close to groundwater uptake wells of the city's drinking water supply station. To protect the ground water quality, only natural surface infiltration is allowed.

Photo 4 A constructed lake with natural surface infiltration.

Tab. 3 Estimated results of a simulation for the planning process, Adlershof project

Estimated project data	*Institute of Physics, HUB, Berlin- Adlershof*	
	Storage capacity:	64 m^3 (15 mm)
	Drinking water supply	> 30 % (Simulation)
	Rainwater for adiabatic cooling:	12 % (Simulation)
	Rainwater for green facades:	26 % (Simulation)
	Rainwater for irrigated courtyards	6 % (Simulation)
	Infiltration into the underground	> 35 % (Simulation)

All data represented are results of a simulation and were generated during the planning process (Tab. 3). Scientific monitoring to determine the overall benefits of the project are beginning immediately.

The retention pond in Adlershof has a size of 1,5% of the annual precipitation. This is quite a low percentage, especially considering its role in water storage for both irrigation and cooling purposes. Many unknown factors – including the amount of water which will be used by the green facade and the adiabatic cooling systems – meant that assumptions had to be made in the planning process. Monitoring of this project will provide information on these subjects that can be used for the planning of future projects.

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