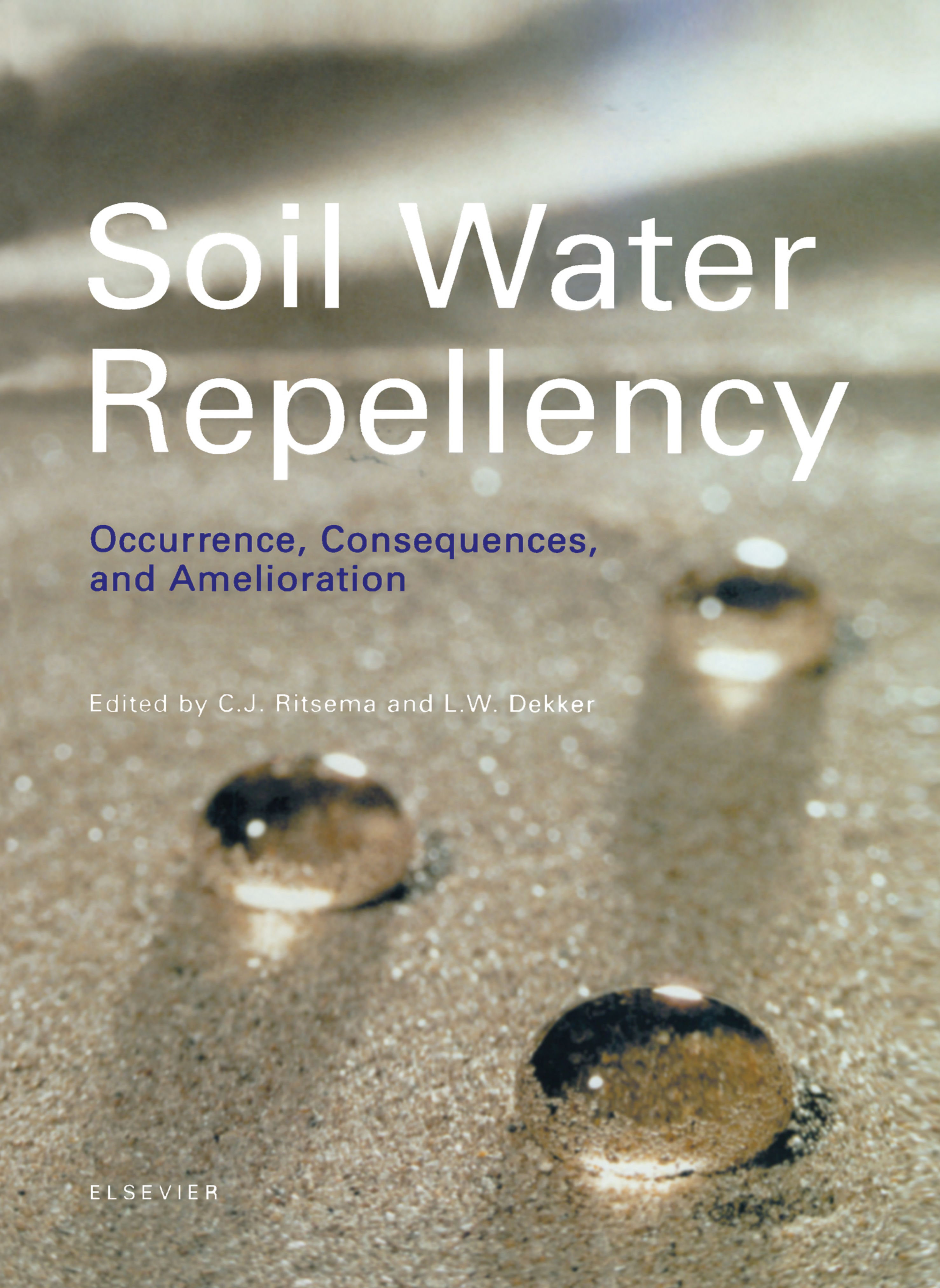

# Soil Water Repellency

## Occurrence, Consequences, and Amelioration

Edited by C.J. Ritsema and L.W. Dekker

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C.J. Ritsema and L.W. Dekker

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# Chapter 1

# Introduction

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Recently, it has become clear that soil water repellency is much more wide-spread than formerly thought. Water repellency has been reported in most continents of the world for varying land uses and climatic conditions. Soil water repellency often leads to severe runoff and erosion, rapid leaching of surface-applied agrichemicals, and losses of water and nutrient availability for crops. At present, no optimum management strategies exist for water repellent soils, focusing on minimizing environmental risks while maintaining crop production. One of the reasons is that knowledge on water repellent soils is scattered among researchers of different disciplines working at different places throughout the world.

To promote cross-disciplinary discussion and to obtain an integral view on many aspects related to soil water repellency, a three-days international workshop had been organized at the DLO Winand Staring Centre for Integrated Land, Soil and Water Research (now Alterra) on September 2–4, 1998. The workshop was sponsored by several institutions and organizations, and was attended by around 150 participants originating from 14 countries. The book starts with a historial overview of water repellency research by DeBano in chapter 2, followed by seven thematic sections covering 26 research chapters.

In the first section dealing with the *the orgin of soil water repellency*, two chapters are presented. In chapter 3, Horne and McIntosh discuss extraction techniques, characterisation methods and proposed mechanisms for water repellency expression. Franco et al. present results on the properties and chemical characterisation of natural water repellent materials in Australian sands in chapter 4.

The second section covers chapters dealing with *the assessment of soil water repellency*. In chapter 5, Letey et al. present an overview of approaches usable for characterizing the degree of water repellency. Bachmann et al. introduce and apply a new sessile drop contact angle method to assess the degree of water repellency in chapter 6, and Wang et al. describe the water-entry value as an alternative indicator of soil water repellency and wettability in chapter 7.

*Occurrence and hydrological implications* of soil water repellency are discussed in the third section of this book. Occurence of water repellency is reported in South Africa by Scott (chapter 8), USA and Colombia by Jaramillo et al. (chapter 9), the Netherlands by Dekker et al., and Dekker and Ritsema (chapters 10 and 15), United Kingdom by York and Canaway (chapter 11), Spain by Moral Garcia et al. (chapter 12), Greece by Ziogas et al. (chapter 13), and Portugal by Doerr and Thomas, and Ferreira et al. (chapters 14 and 16). Effects of the presence of water repellent substances on soil charactistics, vegetation, infiltration, and moisture distribution within the soil are illustrated by most of these authors. Shakesby et al. discuss the erosional impact of soil hydrophobicity, and future research directions in chapter 17.

The fourth section of this book is devoted to the *effect of fire on water repellency*. DeBano presents a

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review on past and current work on the role of fire and soil heating on the inducement of water repellency in wildland environments (chapter 18). The effect of prescribed fire on actual infiltration rates in the field is highlighted by Robichaud in chapter 19.

Section five deals with the *physics and modeling of flow and transport* in water repellent soils. Bauters et al. present a general overview of the underlying physics of water repellent soils in chapter 20. In an experimental study, Clothier et al. illustrate the effect of the breakdown of water repellency on infiltration rates and solute transport in a soil from New Zealand (chapter 21). Wang et al. highlight the effects of soil water repellency on water infiltration rates and the generation of flow instability in the soil profile in chapter 22. Nieber et al. present extensive results of experimental gravity-driven unstable flow in water repellent soils using a two-dimensional numerical simulation model in chapter 23. In chapter 24, Ritsema and Dekker show field evidence and two-dimensional modeling results of finger formation and finger recurrence in a water repellent sandy soil, and, additionally, postulate an alternative approach to incorporate these processes in one-dimensional water flow and transport models.

*Amelioration techniques and farming strategies* to combat soil water repellency are presented in the sixth section. Cann focuses on promoting sustainable agriculture in South Australia by clay spreading on water repellent sands (chapter 25). Dekker et al. discuss the effects of systematic surfactant applications on the amelioration of soil water repellency and soil moisture distributions (chapter 26). Blackwell summarizes management strategies for water repellent soils in Australia in chapter 27, and discusses associated risks of preferential flow, pesticide concentrations and leaching. Abadi Ghadim introduces a whole farm bio-economic perspective for agricultural use of water repellent soils in chapter 28.

Dekker et al. conclude the special issue with an extensive bibliography on soil water repellency research, containing over more than 1000 references (chapter 29). Additional non water repellent references have been listed in Chapter 30.

We would like to express our sincere hope that this first book ever on soil water repellency will act as a stimulus for initiating further research on a broad range of topics related to water repellent soil systems world-wide.

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- The European Union, Grant ENV4-CT97-6129
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# Chapter 2

# Historical overview of soil water repellency

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**Abstract**

The purpose of this paper is to document some of the more important highlights of the research and historical aspects concerning soil water-repellency. This effort traces the evolution of interests and concerns in water repellency from basic studies in the nineteenth century to the earlier part of the 20th century and up to our current-day understanding of this subject. The interactions among different scientific disciplines, various manager-scientists efforts, and specific scientific and management concerns are presented chronologically. This growing interest in water repellency generated an earlier conference in 1968 which was devoted exclusively to water repellency and has since initiated productive discussions and debate on water repellency during several peripherally related national and international conferences. The 1968 conference held in Riverside, California (USA), mainly involved scientists from the United States and Australia. Since this early conference, a large body of information has been published in a wide range of scientific disciplines throughout the world. This worldwide attention has produced many recent research findings, which have improved the understanding of water-repellent soils, particularly of the dynamics of the water movement and redistribution in these unique systems. Intermingled with the effort in water repellency is a related, although somewhat separate, body of information dealing with soil aggregation and water harvesting, which are important for improving the productivity of fragile arid ecosystems. A summary is presented of the literature on water repellency, showing changes in subject areas and national interests over time.

## 1. Introduction

Water repellency has been a concern of both scientists and land managers for well over a century. During this time, the interest in water repellency has evolved from an isolated scientific curiosity to an established field of science that is recognized worldwide. The wide range of topics discussed on this issue exemplify the range of interest in water repellency. The purpose of this paper is to present a detailed overview of the research and institutional history of the field of water repellency. This effort traces the evolution of knowledge and concerns about water repellency from the beginning of this century to our current-day understanding of this subject. The interactions among different scientific disciplines, various manager-scientists efforts, and specific scientific and management concerns are presented both chronologically and by subject area content.

## 2. Information base

The information used as the basis for this paper consisted of: (1) an extensive bibliography of over 500 published papers reporting on various aspects of water repellency; (2) a bibliography of over 200 published papers which contributed information directly related to the understanding of some of the basic physical, biological, and chemical processes—the kind of knowledge essential to the present level of understanding of water repellency phenomena;

and (3) the personal knowledge gained by this author in over 30 years of interest and research in the field of water repellency. The bibliography of related literature was derived mainly from important citations in published papers on water repellency. This list cannot be claimed to be complete, but reflects the author's evaluation of the importance of individual citations and their contributions to the field. The papers cited in this paper represent only a sample of the entire bibliography used and the cited references were selected at the discretion of the author. A comprehensive bibliography is being published separately for those interested in a more complete list of citations.

The bibliography described above was first examined chronologically in order to identify changes in emphasis over time and to track the rise and fall of interest in different scientific and applied aspects of water repellency. This review of literature was also used to identify the evolution of regional emphases on different research topics pertaining to water repellency. The final section of this paper summarizes the chronological development of the knowledge and the regional centers that were involved in water repellency research at different times.

## 3. A global perspective

As during the evolution of many sciences, the earlier years produced only a few publications and the numbers remained low for several decades until interest and fundamental understanding accumulated, after which the numbers of publications mushroomed. Fig. 1 illustrates the number of papers published during different time periods on water repellency per se and in areas that contributed directly to the understanding of water repellency. The total numbers themselves are not too informative, but when examined in detail they reveal some noteworthy landmarks and stages of development. The database provided the basis for identifying the overall flow of information, the emphasis of different topic areas, the reasons for the increased number of publications, and the overall evolution of the science of water repellency. A more detailed review of the chronology of these publications and examples of important

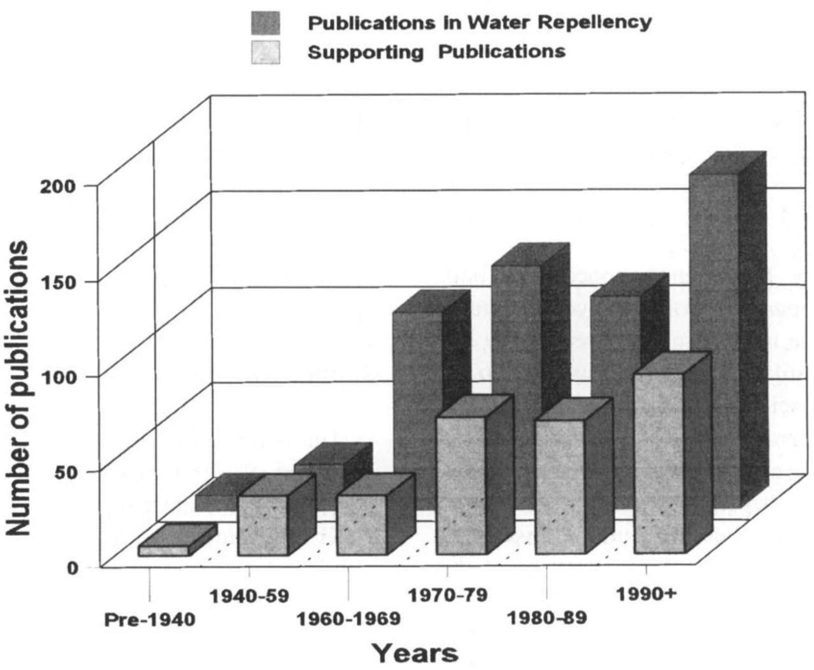


Fig. 1. The number of publications concerning soil water-repellency and related fields during the 20th century.

publications are presented below within the framework of different decades.

## 4. Chronological highlights

The disciplines that provide the scientific and utilitarian basis for our current understanding of water repellency are: firstly, the study of the important role of organic matter in agricultural systems, and secondly, the knowledge of soil–water–plant relationships, particularly the physics of soil water movement. The accumulation of knowledge in these two areas evolved both from academic curiosity and from the importance of organic matter in the productivity of agricultural systems. These two areas of scientific inquiry continued to be keystone sciences underlying the study of water repellency phenomena over the years and also appear as an integral part of many papers included in this issue.

### *4.1. The roots (pre-20th century)*

Interest in water repellency phenomena began well before the 20th century, although it was not identified as such. It is not the purpose of this paper to establish an irrefutable beginning point for the study of water repellency, but instead to identify selected references found in the literature before 1900, which increased the awareness of organic matter (humus) and provided a basis for later studies of water repellency that began in the early 20th century. An examination of the literature before 1900 indicates that water repellency was mostly associated with observations on organic matter and its decomposition, particularly where fungi were involved.

Humic substances were first investigated during the later part of the 18th century when Achard attempted to isolate humic substances in 1786 (Stevenson, 1994). DeSaussure introduced the word "humus" in 1804 and humic acids were designated by Dobereiner in 1822. The first comprehensive reports on the chemical nature of humic substances were written between 1826 and 1862 (Stevenson, 1994). In the second half of the nineteenth century, most of the reports were concerned with classifying products produced during the decomposition of organic substances (Kononova, 1961). By the end of the nineteenth century, it was well established that humus was a complex mixture of organic substances that were mostly colloidal and had weakly acidic properties (Stevenson, 1994).

Studies on the fungal decomposition of organic matter were first reported by Waring in 1837 (as reviewed by Bayliss, 1911) and these reports were probably the first publications that discussed the effect of mycelium growth on the rate of absorption of water by soil. These studies described a phenomenon known as "fairy rings". The term "fairy ring" was used by early investigators to describe the arrangement of plants (usually grass or crop plants) in an approximately circular form, where plant growth on the inside of the circle was stimulated. Circles of bare ground or concentric zones of withered plants surrounded this inner circle of healthy plants. These concentric rings were attributed to various natural and supernatural sources such as the paths created by dancing fairies, thunder, lightning, whirlwinds, ants, moles, haystacks, urine of animals, and so on. In many cases the fairy ring phenomena was so abundant locally that it materially affected the yield of crops. Almost a half century later, quantitative data were reported at Rothamsted indicating that more soil moisture was present in the healthy ring of plants than either outside or inside it (Lawes et al., 1883). Although none of these pre-20th century publications used the term "water repellency", it was obvious that many of these earlier scientists were observing the phenomenon of water repellency as we know it today.

Another building block, which would contribute to the understanding of water repellency, was the discipline of soil physics, which was just starting to appear at the end of the nineteenth century. Two papers written by German scientists during the last part of the nineteenth century described the physics of air and water relationships in soils (Puchner, 1896) and the relationships between rainfall and soil–plant systems (Wollny, 1890). Physical relationships describing the cohesive properties of water had been published much earlier (Young, 1805).

### *4.2. Decades of awareness (from 1900 to 1919)*

Interest in organic matter, particularly humic substances, continued into the earlier part of the 20th century. Starting in 1908, Schreiner and Shorey (1910) initiated a series of studies to identify organic chemicals contained in a California soil. During their investigations of humic substances, they reported studying a soil that "could not be wetted, either by man, by rain, irrigation or movement of water from the subsoil" (Schreiner and Shorey, 1910, p. 9).

During the earlier part of the 20th century the interest in "fairy ring" phenomena continued. Bayliss (1911) reported on the fairy ring phenomena and cited measurements reported earlier by Molliard (1910) that showed that the soil proliferated with fungal mycelium was comparatively dry. The area occupied by the mycelium contained only 5–7% moisture, compared to 21% in the areas inside and outside the ring, which were not occupied by mycelium. Bayliss (1911) validated that soils containing mycelium were difficult to wet and cited an example where rain did not penetrate the soil in mycelia-infested areas but penetrated to a depth of 10 cm in the adjacent non-mycelial areas. Measurements of soil water content, associated with rings formed by a fleshy fungus (*Agaricus tabularis*) that had infected grasslands in eastern Colorado (Schantz and Piemeisel, 1917), indicated that during the spring there were no differences in moisture content between the mycelial and non-mycelial zones. After the soil had dried out in later summer, however, the mycelia-infested soil rings did not permit penetration of water. As a result, large differences in soil water contents were found between the bare areas and the inner and outer vegetated rings, particularly in the upper foot and early in the growing season.

During these first two decades of the 20th century, soil physics and water use by plants began emerging as important sciences. A review of the few studies on soil water movement was published (Buckingham, 1907), as was a report on the importance of transpiration in crop production (Kiesselbach, 1916).

### *4.3. Decades of contemplation (from 1920 to 1939)*

The period between 1920 and 1939 witnessed the development of scientific knowledge in peripheral disciplines that later provided the basis for better describing soil water movement and the physical–chemical nature of wetting. Soil physicists (Zunker, 1930; Richards, 1931) began quantifying the concept of water movement and the importance of capillary forces on water in the soils.

Interest was also developing in the methods of quantifying aggregate stability for erosion control studies (Middleton, 1930). One of the earlier methods of quantifying erosion potential was based on the stability of soil aggregates to slaking when exposed to excess water (Yoder, 1936). The interest in the stability of aggregates to wetting continues today, although more sophisticated procedures are available for assessing this characteristic. More detailed studies on the stability of soil aggregates to wetting were also reported during these two decades, particularly as related to organic matter and microbial processes (Kanivetz and Korneva, 1937; Waksman, 1938).

During these early decades of the 20th century, the physical–chemical nature and the wetting of low surface tension solids (e.g. talcs, waxes and resins) were being investigated from an industrial engineering perspective (Bartell and Zuidema, 1936; Wenzel, 1936).

Only two publications between 1920 and 1939 were found that discussed water repellency. These were: a report of resistance to wetting in sands (Albert and Köhn, 1926), and a second report describing the creation of "ironclad" or artificial catchments (Kenyon, 1929).

### *4.4. Decades of recognition (from 1940 to 1959)*

Between 1940 and 1959, published papers reporting observations on water-repellent soils began appearing in several scientific journals. Studies by Jamison (1946) showed that resistance to wetting was affecting the productivity of citrus orchards in Florida, USA. Elsewhere in the world, Van't Woudt (1959) reported that organic particle coatings were affecting the wettability of soils in New Zealand. The results of an investigation on difficult-to-wet soils was also reported in the Netherlands (Domingo, 1950). Finally, in 1959, detailed microscopic examinations of the aggregating effect of microbiological filaments on the aggregation of sand grains were reported in Australia (Bond, 1959). Although water repellency was not specifically mentioned as being a factor in aggregate stability, this initial publication was the beginning of a series of fruitful research reports about water repellency that was published later by a group of Australian scientists (Bond, Emerson and others) during the 1960s and 1970s.

During these two decades, interest in soil aggregation increased (Robinson and Page, 1950; Martin et al., 1955). This interest included increasing the stability of clay soils (Childs, 1942) using synthetic polyelectrolytes to improve aggregation (Hedrick and Mowry, 1952), and improving aggregation to decrease wind erosion (Chepil, 1958). The role of microorganisms in enhancing aggregation was gaining interest (Martin and Waksman, 1940; Swaby, 1949). Molds and algae were found to be particularly effective agents for soil crusting (Fletcher and Martin, 1948) and aggregation (Gilmour et al., 1948).

An interest in characterizing contact angles also began emerging (Bikerman, 1941) along with a continuing interest in the physical–chemical process of wetting from an chemical engineering perspective (Barr et al., 1948). A book on surface-active agents and detergents was published near the end of these two decades (Schwartz et al., 1958).

Both the theoretical and applied dimensions of water movement in soils were gaining closer attention. Theoretical concepts being developed in soils included: describing capillarity (Miller and Miller, 1956); recognition of contact angles' role during infiltration (Fletcher, 1949); soil water energetics during infiltration (Bodman and Colman, 1943); and the numerical solution of concentration dependent diffusion equations (Philip, 1957). During this same period, viscous flow was described in porous media (Chouke et al., 1959) and in the Hele–Shaw cell (Saffman and Taylor, 1958). These theoretical developments served as the basis for a more comprehensive approach to describing water movement in hard-to-wet soil systems during the following decades. Applied research was done on the effect of plants on interception, stemflow, and ground rainfall (Specht, 1957) and the effect of profile characteristics (Hursh and Hoover, 1941) and roots (Gaiser, 1952) on hydrologic processes in forest soils. Infiltration into soils found in wildland environments was also attracting attention, particularly in soils that had been exposed to wildfires (Scott and Burgy, 1956).

Water repellency was also starting to be utilized for beneficial uses, including its use for water harvesting where paved drainage basins provided a source of water for livestock or game (Humphrey and Shaw, 1957), its application as moisture, thermal and electric insulator during highway construction (Kolyasev and Holodov, 1958), and its potential for decreasing soil water evaporation (Lemon, 1956).

### *4.5. Decade of renewed interest (from 1960 to 1969)*

The decade of the 1960s witnessed a flurry of interest in soil water-repellency and in related fields. As a result, several milestone publications appeared during this decade, in addition to a substantial increase in the knowledge about water repellency in soils and related fields.

#### *4.5.1. Significant milestones*

The first milestone was represented by a surge in the number of scientific papers, primarily by scientists in Australia and the United States, on a wide range of topics concerning water repellency. Between 1960 and 1970, over 90 publications dealing with various aspects of water repellency were published (Fig. 1), with about one-third of these publications appearing in the proceedings of the first international conference at Riverside, CA in 1968 (DeBano and Letey, 1969). An addition of 31 publications reporting scientific findings related to water repellency were also published during this decade.

A second significant milestone during this decade was the development of physical methods for characterizing soil water-repellency using contact angle methodology. In 1962, Letey and coworkers at the University of California, Los Angeles published two significant papers, one describing the measurement of liquid–solid contact angles in soil and sand (Letey et al., 1962a), and a second describing the influence of water–solid contact angles on water movement in soil (Letey et al., 1962b). These publications were closely followed in 1963 by a publication by Emerson and Bond (1963), working in Australia, who described a technique of using the rate of water entry into dry sand to calculate the advancing contact angle.

A third milestone was the summary and synthesis of all available knowledge of water repellency conducted during the 1960s along with earlier findings. This formed the basis for discussion among interested scientists at the first international conference on water repellency held in May 1968 at the University of California, Riverside, USA (DeBano and Letey, 1969). Thirty-one presentations covering a wide range of topics concerning water repellency were discussed at this conference. Specific presentations included: physics of water movement through soil, distribution of water repellency in different ecosystems, theoretical and practical implications of surface-active agents (particularly wetting agents), factors responsible for water repellency (microorganisms and wildland fires), water harvesting, methods of measuring water repellency, and soil erosion processes.

#### *4.5.2. Other advances in water repellency*

The accumulation of knowledge about water repellency and its treatment had accumulated to such an extent during the 1960s that synthesis papers were beginning to be published. Important summary papers included a state-of-the art publication on soil wettability and wetting agents (DeBano et al., 1967), and a separate review describing the chemistry of surface-active agents (Black, 1969). In addition to the synthesis papers, significant papers appeared describing: use of wetting agents to ameliorate water repellency; identification of fire-induced water repellency as a contributor to postfire erosion; interrelationships among organic matter, soil microorganisms and water repellency; and better definition of the role of liquid–solid contact angles in water movement.

The use of wetting agents to increase infiltration and enhance water movement in water-repellent soils attracted considerable attention during the 1960s (Letey et al., 1961; Watson et al., 1969). Particularly noteworthy was a group of scientists and cooperators at the University of Riverside who studied the usefulness of wetting agents for irrigating water-repellent soils (Letey et al., 1962c), established guidelines and techniques for using nonionic wetting agents (Letey et al., 1963), and evaluated the longevity of wetting agents (Osborn et al., 1969a). This interest in wetting agents expanded to their use for reducing postfire erosion (Osborn et al., 1964b) and enhancing turfgrass growth (Morgan et al., 1967). Also, several studies were published about the effects of surfactants on plant growth (Parr and Norman, 1965) and seed germination (Osborn et al., 1967). The increased use of surfactants also prompted an evaluation of their effect on soil aggregation (Mustafa and Letey, 1969).

Large increases in water erosion following wildfires had been a long-standing concern in southern California, USA, particularly in the Los Angles Basin. Research showed that water repellency on these erosive watersheds was intensified by the soil heating occurring during a fire (DeBano and Krammes, 1966). The decrease in infiltration due to water repellency had been overlooked previously by these watershed investigators (Krammes and DeBano, 1965), because it was assumed that the decreased infiltration after fire resulted primarily from the loss of a protective plant cover and the plugging of soil pores with ashy residue remaining on the soil surface. Awareness of fire-induced water repellency in other wildland environments in the United States was quickly reported by other investigators: in forested environments of the Sierra Nevada of Nevada and California (Hussain et al., 1969) and in many vegetation types throughout the western United States (DeBano, 1969a). The relationships among soil fungi, soil heating, and water repellency were also demonstrated (Savage et al., 1969b).

A keen interest in the relationships among organic matter, soil microorganisms, and water repellency also developed during the 1960s. In Australia, research inquiries into the effect of microbial filaments on soil properties were gaining momentum (Bond, 1962). Field studies on water repellent sandy soils (Bond, 1964) revealed that filamentous algae and fungi were responsible for the water repellency (Bond and Harris, 1964). In the United States, the production of water repellency by fungi was also confirmed (Savage et al., 1969b), and the roles of humic acids and polysaccharides were evaluated (Savage et al., 1969a).

The use of hydrophobic materials for harvesting rainfall (water harvesting) attracted substantial interest, particularly in arid regions of the western United States. Water harvesting interests were summarized in reviews, including a description of waterproofing soil to collect precipitation (Myers and Frasier, 1969) and a comprehensive book on waterproofing and water repellency (Moilliet, 1963). A better understanding was also evolving of the chemistry of a variety of synthetic substances that could make soils hydrophobic and of their effect on soil physical properties (Bozer et al., 1969).

Characterizing water repellency and the effect of hydrophobic substances on water movement was the focus of several studies. In addition to the pioneering publications on contact angle methodology described above, fundamental relationships between contact angles of water and saturated hydrocarbons and exchangeable cations were reported (Cervenka et al., 1968). Additional techniques for characterizing water repellency in soils were also reported, including measurements of liquid–solid contact angles (Emerson and Bond, 1963; Yuan and Hammond, 1968). Studies on soil water movement in hydrophobic soils consisted of determining the influence of wetting on the liquid water movement in sand (Vladychenskiy and Rybina, 1965), the role of capillary movement in soils (Wladitchensky, 1966; Rybina, 1967), and the processes of water movement through water-repellent soils (DeBano, 1969b), including layered systems (Mansell, 1969).

#### *4.5.3. Related scientific inquiry*

Numerous publications also appeared during this decade that contributed fundamental knowledge in fields related to water repellency. A comprehensive synthesis of information on the dynamics of aggregation was published (Harris et al., 1966) in addition to a classification of aggregates based on their coherence in water (Emerson, 1967). The role of microorganisms and their byproducts on soil structure stabilization was the focus of some papers (Bond and Harris, 1964; Harris et al., 1964). Polysaccharides were found to play an important role in stabilizing natural aggregates (Acton et al., 1963). Synthetic substances such as 4-tert-butylpyrocatechol were also evaluated for their effectiveness in enhancing soil structural stability (Hemwall and Bozer, 1964). Synthetic soil conditioners were also used to enhance infiltration and reduce erosion (Kijne, 1967).

Basic information that later contributed to understanding water movement in soils began emerging during the 1960s, and provided the basis for describing better the water movement in water repellent systems during the following decades. The theoretical basis for describing infiltration that was developed during the 1950s was summarized (Philip, 1969). Fundamental information on water movement in layered systems was being acquired (Miller and Gardner, 1962). There was also continued interest in the more theoretical aspects of growth by fingers in Hele–Shaw cells (Wooding, 1969). Other important theoretical topics studied during this decade included: development of stability theory for miscible liquid–liquid displacements (Elrick and French, 1966); a better understanding of capillary flow (Waldron et al., 1961); contact angle hysteresis (Johnson and Dettre, 1964) and equilibria (Zisman, 1964); and the linkage between infiltration in sand and ground water recharge (Smith, 1967). The use of surface-active materials (nonionic surfactants, fatty alcohols, hexadeconal) was found to suppress evaporation (Law, 1964) and to alter soil water diffusivity (Gardner, 1969). Two comprehensive reviews were published during this decade, one on soil water theory (Childs, 1967) and a second on contact angle wettability and adhesion (Gould, 1964).

### *4.6. Decade of spinoffs (from 1970 to 1979)*

During the 1970s, over 130 papers were published on various aspects of water repellency and an additional 55 publications on closely related subject matter (Fig. 1). Many of the publications of this decade clearly reflected the spinoffs arising from the information reported at the 1968 conference.

#### *4.6.1. Understanding water repellency*

The interest in water repellency and its management implications began to attract worldwide attention. In the United States water-repellent soils were reported in: desert shrub communities in the American Southwest (Adams et al., 1970); granitic forest soils in the Sierra Mountains of the western United States (Meeuwig, 1971a); pinyon–juniper woodlands (Scholl, 1971), chaparral (Scholl, 1975), and ponderosa pine forests (Zwolinski, 1971; Campbell et al., 1977) in Arizona; mixed conifer forests in California (Agee, 1979); sagebrush-grass communities in the western United States (Salih et al., 1973); the high Cascade Mountains in the northwestern United States (Dyrness, 1976); coal mine spoils of New Mexico (Miyamoto et al., 1977); and forest soils in upper Michigan (Reeder and Jurgensen, 1979) and in Wisconsin (Richardson and Hole, 1978). Elsewhere in the world, water repellency was reported in: Australia (Roberts and Carbon, 1971), Egypt (Bishay and Bakhati, 1976), India (Das and Das, 1972), Japan (Nakaya et al., 1977a), Nepal (Chakrabarti, 1971), Mali (Rietveld, 1978), and New Zealand (John, 1978). The management concerns focused primarily on the effect water repellency had on plant growth, including: the "fairy ring" phenomenon (Stone and Thorp, 1971), impacts on the production of barley (Bond, 1972a), and non-wettable spots on golf greens (Miller and Wilkinson, 1977).

Other interests in water repellency during the 1970s were similar to those during the 1960s and additional research continued to be conducted on: using wetting agents for remedial treatments, fire-induced water repellency, water harvesting, characterizing water repellency, and soil water movement.

*4.6.2. Remedial treatments*

The use of wetting agents and other remedial techniques continued to capture the interest of scientists studying techniques for ameliorating water repellency during this decade. The addition of cores containing a loam soil to water repellent sands was found to increase the overall infiltration rates into sandy soils in Australia (Bond, 1978). Chemical remedial treatments, however, continued to receive most of the attention in treating water-repellent soils. The understanding of wetting agents and/or surfactants challenged both scientists and managers. Noteworthy publications describing the basic functioning of wetting agents in soils included the following topics: factors responsible for increasing the effectiveness of wetting agents (Mustafa and Letey, 1970), quantifying their effect on penetrability and diffusivity relationships in soils (Mustafa and Letey, 1971), evaluating their movement and leaching through wettable and water-repellent soils (Miller et al., 1975), and assessing their effect on pesticide mobility in the soil (Huggenberger et al., 1973). A major concern was the effect of surfactants on plant physiology which led to studies that addressed their effects on: seed germination (Burridge and Jorgensen, 1971); plant cells (Haapala, 1970); growth, porosity, and uptake by barley roots (Valoras et al., 1974a); and the germination and shoot growth of grasses (Miyamoto and Bird, 1978).

Concurrent with the basic studies on wetting agents described above were several reports which emphasized their overall application (Letey, 1975) and their specialized uses in forestry (DeBano and Rice, 1973), including erosion reduction (Valoras et al., 1974b). The success of using wetting agents to remedy water repellency encountered in field situations was variable. In one study, the use of wetting agents improved infiltration into water-repellent coal mine spoils to a limited degree (Miyamoto, 1978). An effort to use operational-level wetting agent treatments to reduce soil erosion on burned watersheds was not successful, however (Rice and Osborn, 1970).

Two important synthesis publications on surfactants were also published during this decade: a state-of-the-art review of soil water-repellency and the use of nonionic wetting agents (Letey et al., 1975) and a book describing the fundamental relationships of surfactants to interfacial phenomena (Rosen, 1978).

*4.6.3. Fire-induced water repellency*

A better understanding of fire-induced water repellency (Savage, 1974; DeBano et al., 1976) and its importance in postfire erosion on watersheds (Megahan and Molitor, 1975) were subjects of active research during the 1970s. Fire-induced water repellency was also reported in different situations, including: under campfires (Fenn et al., 1976); under piles of burned logs (DeByle, 1973), and in the upper soil layers during prescribed fires in mixed conifer forests (Agee, 1979). The author and others present a more detailed discussion of fire-induced water repellency and its erosional consequences elsewhere in this issue.

*4.6.4. Water harvesting*

The use of water repellency principles provided the basis for the rapid expansion of water harvesting technology during the 1970s. Over a dozen published papers dealt with different aspects of water harvesting, including: developing the technology of bonding water repellent films to soil particles (Frasier and Meyers, 1972), assessing the resistance of organo-film-coated soils to infiltration (Fink, 1970), utilizing wax-treated soils for water harvesting (Fink, 1977), developing laboratory evaluation techniques (Fink, 1976), assessing freeze-thaw effects on soils treated for water repellency (Fink and Mitchell, 1975), establishing water harvesting efficiencies for different surface treatments (Rauzi et al., 1973), utilizing water harvesting as a reforestation tool (Mehdizadeh et al., 1978).

Two major efforts to synthesize information on water harvesting occurred during the 1970s. First, a state-of-the-art synthesis on water harvesting was published (Cooley et al., 1975). The second effort was the convening of an international water harvesting conference held in Phoenix, Arizona in 1974 (Frasier, 1975). This conference produced numerous papers on all aspects of water harvesting.

*4.6.5. Characterizing water repellency*

Major advances in characterizing both the physical and chemical nature of water repellency occurred during the 1970s. Investigation of physical effects was concerned with assessing those factors affecting wetting phenomena, while the studies involving chemical characterization of water repellency focused on humic acids and their interactions with various substances, including soils.

Detailed studies were reported on proposed techniques for physically characterizing water repellency in terms of: wetting coefficients (Bahrani et al., 1970), surface roughness (Bond and Hammond, 1970), and liquid-surface tension and liquid–solid contact angles during liquid entry into porous media (Watson et al., 1971). Indices for characterizing water repellency were developed using contact angle–surface tension relationships (Watson and Letey, 1970) and solid–air surface tensions of porous media (Miyamoto and Letey, 1971). Concerns about the limitations of scaling when using contact angles also emerged (Philip, 1971; Parlange, 1974).

A better understanding of the chemistry of hydrophobic substances responsible for water repellency and their interactions with other substances was gained during this decade. A comprehensive book on the chemistry of natural waxes appeared (Kolattukady, 1976). Detailed studies reported on the adsorption of water by soil humic substances (Chen and Schnitzer, 1976) and on the surface tensions of aqueous solutions of soil humic substances (Chen and Schnitzer, 1978). A method was developed to quantify hydrophobic sites on soil minerals using aliphatic alcohols (Tschapek and Wasowki, 1976b). The wettability of different natural substances was being characterized, including that of humic acid and its salts (Tschapek et al., 1973) and of zeolites (Chen, 1976).

*4.6.6. Water movement*

During this decade more was being learned about the effect of hydrophobic substances on soil water movement during infiltration and evaporation (DeBano, 1975). The beneficial use of water repellency to save water (Hillel and Berliner, 1974), particularly by reducing the capillary rise of water to the soil surface where it was evaporated (Hergenhan, 1972), and to reduce fertilizer leaching (Snyder and Ozaki, 1974) also gained attention during the 1970s.

*4.6.7. Related research*

Interest in the interrelationships among aggregation, soil structure, and water repellency was galvanized during the 1970s, when a conference was held in Las Vegas, Nevada, USA, under the sponsorship of the Soil Science Society of America, dealing specifically with "Experimental Methods and Uses of Soil Conditioners" (Stewart et al., 1975). This conference considered soil stabilization to control wind and water erosion, structural improvement of sodic and clay soils, water harvesting, soil conditioning with bentonite, water repellency (water movement, fire-induced water repellency), the role of organic matter and other natural mulches (e.g. bark) to improve soil structure, and the use of synthetic material such as bitumen emulsion and polyacrylamide for soil stabilization. This conference did much to link strongly an independent line of investigations on soil structure and conditioners to those being conducted on water repellency phenomena.

Other important publications on aggregation also were published during the 1970s. Fundamental work on cementing substances of iron and aluminum on soil aggregates was being published in Italy by Giovannini and Sequi (1976b) and interest continued about the role of microorganisms in stabilizing aggregates (Aspiras et al., 1971b). A book on modification of soil structure, including chapters on aggregate formation and stabilization, was also published (Emerson et al., 1978).

Important theoretical efforts by soil physicists began identifying more realistic models for describing soil water movement in water repellent systems.