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Review

Water repellency in soils: a historical overview

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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. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Water repellency in soils; Historical highlights of research; Manager-scientists efforts

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

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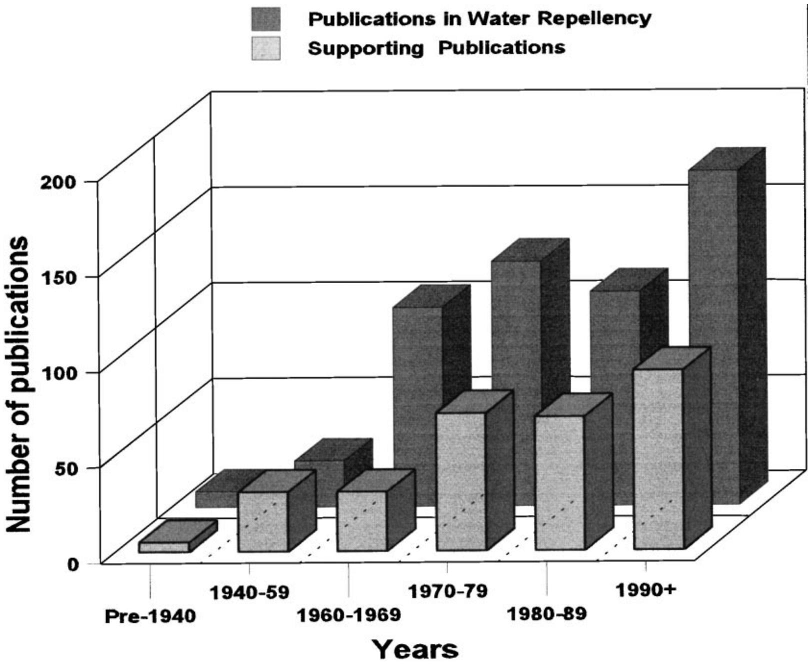

Fig. 1. The number of publications concerning soil water-repellency and related fields during the 20th century.

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 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 (Stevensen, 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 (Stevensen, 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 (Stevensen, 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 (Shantz 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 (1947) 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., 1969). This interest in wetting agents expanded to their use for reducing postfire erosion (Osborn et al., 1964) 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 equlibria (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, 1971); 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., 1977), 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, 1972), and non-wettable spots on gold 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, 1976). 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 (1976) and interest continued about the role of microorganisms in stabilizing aggregates (Aspiras et al., 1971). 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. Foundations were established for describing the hydrodynamic instability of miscible fluids in porous media (Bachmat and Elrick, 1970), solving flow equations for unsaturated soils (Parlange, 1975), and determining the extent of equilibrium vapor adsorption by water-repellent soils (Miyamoto et al., 1972). The complications arising from wetting front instability and unstable flow in layered soils were beginning to be more fully recognized (Hillel, 1972; Hill and Parlange, 1972) and a theoretical framework for analyzing wetting front instability was proposed (Parlange and Hill, 1976). Experimental studies were also conducted on the effect of sudden changes in pressure gradients on wetting front instability in heterogeneous media (White et al., 1977); spatial variability in field-measured water properties (Nielsen et al., 1973); and unstable flow during infiltration (Raats, 1973; Philip, 1975). Preferential flow through large pores was also receiving attention (Ehlers, 1975; Scotter, 1978). A conceptual model for hysteresis was described (Mualem, 1974).

4.7. Decade of enrichment (from 1980 to 1989)

The decade starting in 1980 was characterized not only by continuing strong interest in water repellency per se, but also saw the development of knowledge in related areas which would be used during the 1990s as the basis for describing water movement in hard-to-wet soils. Over 150 publications on water repellency appeared during this decade; in addition, more than 55 papers describing related theory were published (Fig. 1).

The decade began with a state-of-the-art publication, which synthesized much of the published information on water-repellent soils up through the mid-1970s (DeBano, 1981). The management concerns enlarged from a limited focus on the effects of water-repellent soils on plant productivity during the 1960s and 1970s, to more complicated and broader environmental issues in the 1980s. These emerging management concerns prompted the initiation of a wide spectrum of new research.

4.7.1. Understanding water repellency

Water repellency continued to be reported as a problem when managing sandy and heavy textured soils in: Australia (McGhie and Posner, 1980; Ma'shum and Farmer, 1985), Japan (Nakaya, 1982), Poland (Prusinkiewicz and Kosakowski, 1986), and the United States (Hubbell, 1988). Numerous publications continued to address the concerns with the wettability of golf greens as related to thatch and dry patch in: Australia (Charters, 1980), Great Britain (Shiels, 1982), New Zealand (Wallis et al., 1989), and the United States (Taylor and Blake, 1982). The effect of plant shoot material on the development of water repellency was also examined (McGhie and Posner, 1981).

The wettability of humus and peat materials was found to be an important factor in managing forested ecosystems. Humus wettability had to be considered when managing forests in Poland (Grelewicz and Plichta, 1985). Interest in the management of peat bogs was highlighted by a book on peat and water (Fuchsman, 1986). Of special interest were studies on the effect of mineralization on the hydrophilic properties of peat soils when managing peat bogs (Lishtvan and Zuyev, 1983).

Several areas of water repellency studied during the 1960s and 1970s continued to attract interest during the 1980s. These include: remedial treatments, fire-induced water repellency, characterizing water repellency, soil structure and aggregation, and the effect of water repellency on soil water movement.

4.7.2. Remedial treatments

Remedial treatments captured the interest of several authors. Application of surfactants was by far the most popular treatment (Rieke, 1981; Sawada et al., 1989). The use of dispersible clays, however, was emerging as a promising technique for reducing water repellency in sandy soils in Australia (Ma'shum et al., 1989). Physical methods of ameliorating water repellency other than claying were to emerge later during the 1990s when they would become efficient and widespread methods for treating water repellency, particularly in Australia and New Zealand.

4.7.3. Fire-induced water repellency

The interest in the effect of fire-induced water repellency continued and in the 1980s it was reported in: California (Wells, 1987), Canada (Henderson and Golding, 1983), southern Chile (Ellies, 1983); Calluna heathlands in England (Mallik and Rahman, 1985), Italy (Giovannini and Lucchesi, 1983), Oregon (McNabb et al., 1989), the Pacific Northwest of the USA (Poff, 1989), South Africa (Scott, 1988), Spain (Almendros et al., 1988), and Turkey (Sengonul, 1984).

The effect of water-repellent soils on erosion from burned watersheds continued to capture the interest of several investigators. A conceptual model relating hillside rill erosion to the formation of a water-repellent soil layer during fire was developed for chaparral areas in southern California (Wells, 1987). The Universal Soil Loss Equation (USLE) was evaluated on burned forest areas in northwestern Spain (Diaz-Fierros et al., 1987).

4.7.4. Characterizing water repellency

Assessing and quantifying water repellency also remained a continuing interest. Publications during this decade included those on the methods for measuring severity of water repellency (King, 1981), field techniques for quantifying water repellency using soil survey information (Richardson, 1984), the use of effective contact angle and water drop penetration time to classify water repellency (Wessell, 1988), and measurement of water repellency using intrinsic sorptivity measurements (Tillman et al., 1989). The effect of humidity on water repellency was also assessed (Jex et al., 1985).

4.7.5. Soil aggregation and structure

Soil aggregation and its stability remained a popular subject of many studies. An energy-based index was developed for assessing the stability of soil structure (Skidmore and Powers, 1982). The importance and overall role of organic matter in the structural stability of soil aggregates was discussed by some authors (Chaney and Swift, 1984; Oades, 1984). Still other authors focused specifically on the effect of humic substances on the stability of soil aggregates (Chaney and Swift, 1986; Piccolo and Mbagwu, 1989).

Significant research results continued to be published on water repellency and aggregation stability (Giovannini and Lucchesi, 1983) and on the identification of substances responsible for hydrophobicity in soils (Giovannini and Lucchesi, 1984; Ma'shum et al., 1988). Lastly, a comprehensive review was published in a book describing the interactions between microorganisms and soil minerals (Huang and Schintzer, 1986).

4.7.6. Water movement in soils

During the decade starting in 1980, substantial progress was made in establishing the theoretical basis for describing water flow through water repellent systems. This theoretical framework provided the basis for making substantial progress in describing water movement in hydrophobic soils later during the 1990s.

During the 1980s, the theoretical developments in the field of fluid dynamics which described fingering phenomena in the Hele–Shaw cells were published (Saffman, 1986). These theoretical developments provided the basis for extending the concept of fingering to describe water movement in soils. Hillel and Baker (1988) presented a descriptive theory of fingering during infiltration in layered soils, which was expanded to describe fingering phenomena in two-dimensional, homogeneous, unsaturated porous media (Tamai et al., 1987). Preferential flow patterns were being reported regularly in agricultural soils (Van Ommen et al., 1988).

Concurrent with the interest in fingering phenomena described above were reports on the stability of water movement through unsaturated porous media (Diment and Watson, 1985), particularly in the vadose zone (Glass et al., 1988), which led to a suggested mechanism for finger persistence in homogeneous, unsaturated porous media (Glass et al., 1989). Fundamental studies were also conducted to assess penetration coefficients in porous media (Malik et al., 1981). Characterization of sorptivity and soil water diffusivity was being expanded to describe these processes under field conditions (Clothier and White, 1981). Subsurface flow processes were also being evaluated above fragipan horizons (Parlange et al., 1989) and in forest soils (Mosely, 1982).

A successful climax to the research efforts on soil movement in unsaturated soil was the convening of an international conference in New Mexico that was devoted entirely to examining flow and transport models used to characterize water flow in unsaturated zones (Wieringa and Bachelet, 1998). One of the papers at this conference extended recent soil water theory to describe water and solute movement through water repellent sands (Hendrickx et al., 1988).

4.7.7. Miscellaneous research

In addition to the areas of interest discussed above, some miscellaneous information on water repellency was also published during the 1980s. One such study described relationship of vegetation age to soil water-repellency in California chaparral ecosystems (Teramura, 1980). Water repellency was also reported to be an important factor in the reclamation of soils containing degraded lignite (Richardson and Wollenhaupt, 1983). Water repellency was reported in coastal sand dunes of the Netherlands where its presence affected the erosion processes on sand dune landscapes (Jungerius and Van Der Meulen, 1988). Finally, the role of hydrophobic substances was evaluated in the adaptation of leaves to periodic submersion by tidal water in a mangrove ecosystem (Misra et al., 1984).

4.7.8. Related research

The increased environmental awareness during the 1980s began to capture the interest of several soil scientists. Of particular concern was the rapid movement of contaminants into the groundwater via preferential flow patterns. Although most of the early efforts were concentrated on developing new theoretical approaches to infiltration and water movement through soils, this effort evolved into the theoretical and operational frameworks necessary for quantifying the effect of water repellency on groundwater contamination later during the 1990’s. This approach, therefore, provided an initial stimulus for attacking the complex process of ultimately merging surface hydrologic theory with models describing integrated soil–water systems.

4.7.8.1. Surface hydrology. Surface hydrology and watershed performance began emerging as major interests during the 1980s (Beven, 1989); some of this work had a direct bearing on the effect of water repellency on catchment responses. Theoretical work on surface hydrology focused on lateral flow through layered soils on sloping topography was beginning to appear in the literature (Zaslavsky and Sinai, 1981; Selim, 1987; Miyazaki, 1988). Detailed evaluations were also made of unsaturated and saturated flow through a thin porous layer on hillslopes (Hurley and Pantelis, 1985). Concurrent with this interest in surface hydrology was the interest in extending the principles of water repellency to erosion and hydrologic performance on a watershed level (Topalidis, 1984; Burch et al., 1989).

4.7.8.2. Integrated soil water systems. Concerns intensified during the 1980s about the rapid transport of pollutants from the soil surface through the soil into the underlying ground water. Stemflow was quickly recognized as an important mechanism capable of delivering rainfall rapidly to the soil surface (Van Elewijck, 1989). Once the water had been delivered to the soil surface, macropores and other discontinuities in the soil provided pathways that quickly moved water, containing dissolved and suspended matter along with adsorbed contaminants, through the soil into the underlying water table (Beven and Germann, 1982; Bouma, 1982). Specific examples of such processes included nitrogen leaching during sprinkler irrigation (Dekker and Bouma, 1984); chloride movement through a layered field soil (Starr et al., 1986); and the movement of water and solute pollutants through unsaturated zones (Raats, 1984). The rapidly growing interest in the storage and movement of materials in soils, particularly pollutants, resulted in a special publication describing the reaction and movement of organic chemicals in soils (Sawhney and Brown, 1989). Fundamental studies were also conducted on developing models to describe adsorption and transport of hydrophobic organic chemicals in aqueous and mixed solvent systems (Rao et al., 1985) and in natural sediments and soils (Karickhoff, 1981).

4.8. Decade of maturity (from 1990 to 1998)

Between 1990 and 1998, a record breaking 150, or more, papers on water repellency and over 60 additional papers on related subjects were published (Fig. 1). Substantial progress was made in all aspects of water repellency, although the increased understanding of water movement through these hard-to-wet systems was particularly noteworthy. The publications concerned with water movement reflected a close cooperative effort between scientists working on the cutting edge of soil physics and scientists concerned with water repellency phenomena.

4.8.1. Occurrence and amelioration of water repellency

The 1990s also witnessed a more profound recognition of the implications of water-repellent soils on the productivity of both cultivated and natural ecosystems, as well as recognition of their role in emerging environmental issues. This increased awareness led to a concerted effort to manage and/or ameliorate the adverse effects of water repellency.

4.8.1.1. Occurrence. During the 1990s, water repellency continued to be reported to occur in a wide range of natural and agricultural environments and as a result was fast becoming an important component in the management and productivity of soils worldwide during the 1990s. The most frequent reports described problems on agricultural lands. The effect of water repellent sands on crop and pasture production was particularly acute on thousands of hectares in Australia and New Zealand, where the importance of this problem stimulated intensive research on the problem and intensified a search for economic methods of ameliorating this soil condition. (Blackwell, 1993; Carter and Howes, 1994). As a result, studies on the physiochemical and biological mechanisms responsible for water repellency in sands were initiated (Franco et al., 1994), as were studies on the role of particulate organic matter (Franco et al., 1995). In the Netherlands, special concerns arose about ground water contamination with fertilizers and pesticides that had been transport rapidly downward through wettable fingers in an otherwise water-repellent soil (Van Dam et al., 1990).

Other, less widespread, interest on water repellency was also reported. Localized areas of highly water-repellent soils were created by oil spills, thus requiring intensive remedial efforts (Roy and McGill, 1998). Furthermore, water repellency was also becoming recognized as a key mechanism responsible for the self-cleaning features of plant surfaces (Neinhuis and Barthlott, 1997). The diminished aesthetics and playing qualities of golf greens that were afflicted by the age-old problem of “dry patch” still concerned golf green supervisors (Tucker et al., 1990; York and Baldwin, 1992; Hudson et al., 1994).

Water repellency was also reported in wildland soils (i.e. uncultivated soils supporting natural stands of trees, shrubs, and grass), both in fire and non-fire environments. Water-repellent soils were reported in several wildland environments, including: dry sclerophyll eucalyptus in Australia (Crockford et al., 1991), eucalyptus and pine forests in Portugal (Doerr et al., 1996), eucalyptus forests in South Africa (Scott, 1991), and under windbreaks in Taiwan (Lin et al., 1996). The fire-induced water repellency described above continued to have its primary impact on wildland ecosystems.

4.8.1.2. Amelioration. Coping with water-repellent soils continued to present a challenge to managers of agricultural and pasture lands worldwide (Abadi, 1994; Capriel, 1997). Interest in the usefulness of wetting agents as a remedial treatment for water repellency continued (Effron et al., 1990), although it did not capture as much interest as during the 1960s and 1970s. Wetting agents were also used to enhance irrigation (Wallis et al., 1990) and drainage (Zartman and Bartsch, 1990). Their effects were studied on aggregation and colloidal stability in tropical soils (Mbagwu et al., 1993).

Remedial treatments other than wetting agents were beginning to be tested and used more extensively, particularly in Australia and New Zealand (Carter and Howes, 1994). These treatments included: direct drilling (Chan, 1992), wide furrow sowing (Blackwell et al., 1994b; Blackwell and Morrow, 1997), and the use of microorganisms (Roper, 1994) and fertilizers to stimulate microbial breakdown of water repellency (Michelson and Franco, 1994). Soil claying, a treatment involving mixing large amounts of clay in the upper water repellent layer, received widespread use in Australia (Blackwell et al., 1994c; Carter and Hetherington, 1994; Dellar et al., 1994). Intensive examinations were made of the effect of clay mineralogy and exchangeable cations on water-repellent soils that had been amended with clay (Ward and Oades, 1993). High pH soil treatments offered some alleviation of the hydrophobic condition found on golf greens (Karnok et al., 1993).

4.8.2. Water movement in soils

Water movement into and through water-repellent soils was a major focus of research during the 1990s. This effort involved the creation of a forum for exchanging and assessing relevant information among scientists (e.g. workshops, conferences), utilizing cutting-edge soil water theory for describing water movement in water-repellent soils, and identifying the role of water repellency in present-day environmental issues.

4.8.3. Information exchange

A significant landmark for this decade was the bringing together of the theoretical and practical dimensions of distribution flow and fingering phenomena, as studied during the early 1990s, the 1980s, and earlier, during a one-day workshop held at the Winand Staring Centre in Wageningen in April 1994 (Steenhuis et al., 1996). During this workshop, 14 papers were presented on various aspects of water repellency and supporting theoretical sciences. This collection of papers included several on characterizing field moisture patterns in water-repellent soils, on the three-dimensional portrayal of preferential flow patterns, and on the use of ground-penetrating radar for identifying structural layers that affect finger flow phenomena. Theoretical papers reviewed the instability of fingered flow and the heterogeneity of these fingers. Another paper described the field validation of laboratory-based equations for determining finger dimensions. The use of laboratory theory to predict the risk of ground water contamination was also presented. A final set of papers presented various models describing: instability-driven fingers, finger formation based on laboratory findings, and heterogeneity-driven fingers. These presentations were combined into one document and were published in 1996, vol. 70, no. 2–4, of Geoderma.

Numerous additional papers were published on the theoretical and applied aspects of water movement per se. The application of such theoretical analyses to describing water movement in hard-to-wet soil systems both in laboratory and field environments was particularly useful. Preferential flow was of such importance that a national symposium was devoted to this subject at Chicago, Illinois in 1991 (Gish and Shirmohammadi, 1991).

4.8.4. Theoretical development

In addition to the papers presented at the Wageningen and Chicago conferences, numerous other papers appeared which described theoretical studies done on the transport of water and associated solutes through the soil. These reports described the instability of wetting fronts during infiltration into unsaturated porous media (Glass et al., 1990; Selker et al., 1992a), infiltration into layered soils (Baker and Hillel, 1990; Steenhuis et al., 1991), preferential and lateral flow (Kung, 1990a,b; Heijs et al., 1996), fingered flow (Selker et al., 1992b,c; Glass and Nicholl, 1996; Nieber, 1996), and the complications arising from hysteresis in soil–water systems (McCord et al., 1991). Other studies focused on the effect of different moisture contents on the formation and persistence of fingered flow in coarse-grained soils (Liu et al., 1994a) and outlined closed-form solutions for predicting finger width development in these soils (Liu et al., 1994b).

A better understanding of the theoretical basis of distribution flow, unstable moisture movement, and fingering phenomena was quickly extended to describe water movement through water repellent systems. Detailed field measurements had established that uneven moisture patterns developed as a result of water repellent sites throughout the soil profile (Dekker and Ritsema, 1994a). The theoretical models describing fingering and instability of wetting fronts began to be applied intensively to describe the water movement in the water-repellent soils, particularly by scientists in the Netherlands or their cooperators (Hendrickx et al., 1993; Dekker and Ritsema, 1995, 1996a; Ritsema et al., 1998), the dynamics of finger (or preferential) flow in water repellent systems (Ritsema et al., 1993, 1996, 1997a,b; Ritsema and Dekker, 1994; Dekker and Ritsema, 1996b; Bauters et al., 1998), the contribution of finger flow to solute movement through the soil (Van Dam et al., 1990), and water movement through macropores in soils (Mallants et al., 1996). Distribution flow was demonstrated to be an important process in the top layer of water-repellent soils (Ritsema and Dekker, 1995) that directed surface-applied water to preferrential flow paths within the soil profile (Ritsema and Dekker, 1996a). Studies were designed to predict the occurrence and diameters of fingers occurring in field soils (Ritsema et al., 1996) and to examine the recurrence of fingered flow pathways through water repellent field soils (Ritsema and Dekker, 1998a). The effect of cover type on preferential flow and resulting moisture patterns in water-repellent soils was studied under field conditions (Dekker and Ritsema, 1995, 1996b, 1997). The information gained by the above studies served as the basis for modeling finger formation and recurrence (Ritsema et al., 1998), and three-dimensional fingered flow patterns (Ritsema et al., 1997a; Ritsema and Dekker, 1998b). The role of hysteresis when describing unsaturated flow in water-repellent soils was reported (Van Dam et al., 1996). A numerical model was developed for describing the movement of heat and water in water repellent sands that were furrowed for remedial purposes (Yang et al., 1996).

4.8.5. Environmental implications

The awareness of environmental issues emerging during the previous two decades lead to several studies during the 1990s that examined the role of water repellency within the context of environmental management. The most apparent need was for developing models describing the transport of field-applied chemicals through the soil (Flühler et al., 1996). Estimates of pollutant loading via fingered flow were reported (Selker et al., 1991). Information on water and chemical transport was used as the basis for developing a soil classification system that reflected these processes (Quisenberry et al., 1993). The role of solute leaching was beginning to be modeled for water-repellent soils (De Rooij and De Vries, 1996). The movement of contaminants via finger flow (Selker et al., 1991) was particularly important in water repellent sandy soils (Van Dam et al., 1990).

Also, adsorption of hydrophobic substances on soil and sediments was receiving attention for at least two reasons. First, the adsorption of hydrophobic substances was necessary for inducing permanent water repellency for water harvesting purposes (Blackwell et al., 1994a), which had received considerable attention in the 1970s. Secondly, the adsorption and transport of hydrophobic contaminants by soils and sediments was emerging as a sensitive environmental concern (Ghosh and Keinath, 1994; Huang et al., 1998; Weber et al., 1998).

4.8.6. Surface hydrology and watershed responses

During the 1990s, initial efforts were made to extend the soil water theory described above to surface hydrology of hillslopes and even further to describe entire watershed responses.

4.8.6.1. Surface hydrology. Surface hydrology drew the interest of some investigators. Models were developed to describe infiltration, soil moisture, and unsaturated flow (Beven, 1991a) and were expanded into a conceptual approach for predicting runoff (Beven, 1991b). The concepts of hysteresis and state-dependent anisotrophy were being incorporated into the modeling of unsaturated hillslope hydrologic processes (McCord et al., 1991). Important hydrologic relationships in unsaturated air systems and their role in contaminant transport were also receiving attention (Scanlon et al., 1997).

4.8.6.2. Watershed responses. Hydrologic responses of watersheds, particularly after fire, gained special attention during the 1990s. Theoretical work on predicting the relationships among infiltration, unsaturated flow, and runoff was reported for unburned watersheds (Beven, 1991a,b). There was particular interest in quantifying the hydrologic processes involved in subsurface transport from an upper subcatchment during storm events (Wilson et al., 1991), including hillslope infiltration and lateral downslope unsaturated flow (Jackson, 1992). Recent advances in modeling of hydrologic systems also served as the theme of a book (Bowles and O'Connell, 1991).

Watershed behavior and hydrologic responses to wildfire and changes in soil wettability received considerable attention by investigators in Africa (Scott, 1997), Portugal (Shakesby et al., 1993; Walsh et al., 1994), Spain (Imeson et al., 1992) and the United States (Robichaud, 1996).

Water repellency was recognized as playing an increasingly important role in erosional processes. In non-fire environments, water repellency induced erosion in dunes along the coast of the Netherlands (Jungerius and Dekker, 1990; Witter et al., 1991). Raindrop splash was recognized as an important process during the erosion of both hydrophobic and wettable soils (Terry and Shakesby, 1993). Special attention was also directed toward modeling the spatial variability in hillslope erosion following timber harvesting and prescribed burning (Robichaud, 1996). Comparisons of experimental results with those predicted by the Water Erosion Prediction Program (WEPP) models showed reasonable accuracy, although the WEPP model showed a consistent tendency to underestimate runoff and erosion (Soto and Diaz-Fierros, 1998).

4.8.7. Fire-induced water repellency

There was a continuing interest in determining the heat-induced changes that occur in soils during fire in natural ecosystems (Soto et al., 1991; Giovannini, 1994; Sala and Rubio, 1994) and in the associated creation of water repellency (bibliography by Kalendovsky and Cannon, 1997). Changes in soil water-repellency in response to soil heating during fire were reported for several ecosystems, including: pinyon–juniper woodlands in the United States (Everett et al., 1995), forests in Spain (Almendros et al., 1990), eucalyptus forests in Portugal (Walsh et al., 1994; Doerr et al., 1998), and chaparral in the United Sates (DeBano et al., 1998). Fire effects studies on closely related changes included studies on the effect of fire intensity on soil changes (Giovannini and Lucchesi, 1997), the overall changes in soil quality produced by fire (Giovannini, 1994), and fire-induced changes in aggregate stability (Molina et al., 1991).

4.8.8. Characterizing water repellency

A wide range of approaches were used to characterize water repellency, including: evaluating traditional methodologies; utilizing new analytic techniques; and designing statistical sampling designs to better describe and assess overall water repellency under field-scale conditions.

4.8.8.1. Traditional and new methodologies. Specific techniques were evaluated, included using intrinsic sorptivity as an index for assessing water repellency (Wallis et al., 1991) and standardizing the "water drop penetration time" and the "molarity of an ethanol droplet" techniques to classify soil hydrophobicity (Doerr, 1998). A method of characterizing disaggregated nonwettable surface soils found at old crude oil spill sites was also reported (Roy and McGill, 1998). A detailed examination was made of the relationship between water repellency, measured in the sieve fractions of sandy soils containing organic matter, and soil structure (Bisdom et al., 1993).

A need to better designate the differences between "potential" and "actual" water repellency and to establish a "critical soil water content" when assessing water repellency was identified (Dekker and Ritsema, 1994a). The water repellency of an oven-dried sample is designated as "potential", in contrast to the water repellency of a field moist sample which is referred to as "actual". The need to distinguish between the two arises because water repellency is a time-dependent soil property and wetting resistance decreases with time, particularly when the soil is exposed to high humidity or water. These changes make static measurements of water repellency inadequate (Dekker and Ritsema, 1994b).

Several new analytical and visualization techniques were reported which could potentially improve the assessment of water repellency and its effect on soil water movement. One such technique is the use of computed tomographs as a tool for non-destructive analysis of flow patterns in macroporous clay (Heijs et al., 1995). Time Domain Reflectometry (TDR) employing standard three-rod probes was also used to measure volumetric water contents at different times and positions in the soil profile (Ritsema et al., 1997a). A visualization techniques, useful for more vividly portraying three-dimensional finger flow patterns, was generated using modular visualization software and associated computer hardware (Heijs et al., 1996; Ritsema et al., 1997a). Another promising technique was the use of NMR (nuclear magnetic resonance) to quantify and study organic matter in whole soils (Preston, 1996). Furthermore, a more detailed chemical analysis of organic matter using reflectance Fourier transform infrared spectroscopy (DRIFT) was tested as a potential tool for characterizing water repellency by providing aliphatic C–H-to-organic C ratios (Capriel et al., 1995). A higher ratio indicated greater water repellency.

4.8.8.2. Sampling and landscape characterization. The importance of sampling, characterizing, and portraying the spatial distribution of water repellency under field conditions received the attention of several investigators. Spatial variability of soil hydrophobicity was studied in fire-prone eucalyptus and pine forests in Portugal (Doerr et al., 1996, 1998). A detailed study was conducted on the influence of sampling strategy on detecting preferential flow paths in water-repellent sand (Ritsema and Dekker, 1996b). It was found that as the physical size of the soil sample increase, the detection of detailed preferential flow patterns diminished until they were eventually unobservable. Therefore, because preferential flow patterns vary in space and time, the optimal number of samples to detect these paths varied, indicating that sampling strategies needed to be flexible in design.

There is an emerging interest in characterizing water repellency on a landscape basis. Such a relationship would involve first relating specific soil properties to water repellency (McKissock et al., 1997), and then using the spatial distribution of these diagnostic soil parameters to predict the occurrence of water repellency over large landscapes (Harper and Gilkes, 1994).

4.8.9. Summary publications

The 1990s also were highlighted by several summary publications on water repellency, or closely related subjects. These included a state-of-the-art publication on water repellency (Wallis and Horne, 1992). The proceedings for two conferences in Australia also appeared, one held in 1990 in Adelaide (Oades and Blackwell, 1990) and the Second National Water Repellency Workshop held at Perth in 1994 (Carter and Howes, 1994). In addition, an international conference on soil erosion and degradation as a consequence of forest fires was held in Barcelona, Spain in 1991, with the proceedings published in 1994 (Sala and Rubio, 1994).

The two regional conferences in Australia brought together an excellent review of the ongoing research and application of knowledge being conducted there. Topics discussed at the 1990 conference included a review of the historical problems created by water repellency; the physics of water-repellent soils; the chemistry of water repellency; the effect of water-repellent soils on wind erosion of sand soils; and the use of a furrow sowing press wheel, wetting agents, additions of clays, and plants to ameliorate water repellency. The second conference in 1994 expanded on the earlier conference and the topics discussed were: causes and extent of water repellency, biological control of water repellency, the use of furrow sowing techniques to improve infiltration, farmer experiences when managing water-repellent soils, amelioration of water repellency with soil additives (e.g. claying), economic impact of water repellency on farm management, and establishment of perennial pastures on water repellent sands (Carter and Howes, 1994).

The Barcelona conference was concerned with fire effects, particularly on erosion and soil degradation. Many of the papers discussed fire-induced water repellency and erosion processes following the fire. The important topics that were discussed were the action of forest fires on: vegetative cover and soil erosion, soil quality, physical and chemical properties of the soil, changes in aggregate stability, and overall post-fire management and erosion response.

5. Summary

The body of knowledge concerning water repellency has evolved from a little known academic curiosity arising during vegetation studies in the early 1900s to a highly complex field of study during the 1990s. Early in the 1900s, scientists began reporting hard-to-wet soils, especially those associated with the “fairy ring” or “dry patch” phenomenon. Restricted water infiltration and redistribution in water-repellent soils and their effect on the productivity of horticultural crops, citrus trees, pasture production, and turf management were of concern to managers, starting in the 1940s and continuing to the present. Concerns over runoff and erosion from wildlands, particularly following fires, attracted concentrated interest in the 1960s and 1970s. This stimulated interest in studying the entire soil–water system and led to methods of characterizing water repellency in terms of water penetration, liquid-solid contact angles, and eventually the dynamics of both laboratory and field soil water systems. The concern with restricted water movement in soil led to a concurrent effort to develop mitigating techniques that would improve plant productivity and reduce runoff and erosion.

The past 30 years have witnessed an ever-increasing interest in water repellency. This evolving interest has shifted the centers of research and the areas of interest concerning water repellency in soil. During the 1940s and 1950s, the primary pragmatic interest was in citrus production in Florida, USA, although “bare patch” disease was reported in clover pastures in south Australia. In the 1960s, water-repellent soils became a high profile concern both in southern California, USA and in Australia. In the United States, a substantial research effort on water repellency by faculty and graduate students at the University of California, Riverside (UCR) focused on developing contact angle theory to characterize water repellency and also on applying remedial wetting agent treatments to increase infiltration rates into water-repellent soils. Working closely with the UCR group was a small group of USDA Forest Service scientists working on fire-induced water repellency and post-fire erosion on the San Dimas Experiment Forest in southern California. Simultaneously, during the 1960s, a concerted effort was being conducted on the other side of the world by Australian scientists, who were concentrating on understanding microbial effects on soil physical properties, including water repellency in sandy soils and is effect on pasture productivity. The worldwide interest at this point in time was reviewed and synthesized at the first international conference on water repellency at Riverside, CA in June of 1968.

The 1970s witnessed an awakening to the worldwide occurrence of water repellency and as such was titled the decade of "spinoffs" Water repellency was reported in a wide range of agricultural and natural environments. During this decade there was a concentrated interest in the use of wetting agents as a remedial treatment for water-repellent soils. The research and technology necessary to implement water harvesting techniques were well established during this decade and their application continues to occur worldwide up to the present. Another significant occurrences during the 1970s was the bridging of interests of scientists working on aggregation and on water-repellent soils during a special conference on soil conditioners. Significant advances in soil physics relationships describing the instability of flow in homogeneous and layered systems provided the background for implementing these concepts in the following decades. The study of hysteresis and preferential flow through macropores was in its infancy and just beginning to attract the serious attention of scientists interested in water movement in soils.

The decade of the 1980s experienced a combination of the old and the new. The age-old concerns with "dry patch" and fire-induced water repellency remained. However, some new aspects of water repellency began emerging, including an interest in the wetting of peat soils and organic forest soils. Most noteworthy were the advances that were being made in understanding surface hydrology and water movement through soils. A great deal of theoretical work on lateral flow in sloping and layered soils was beginning to make its appearance. These developments had important implications in describing catchment responses. New approaches for describing soil water movement in non-uniform systems were rapidly being developed. The first reports on the concept of water movement through porous media by fingering were beginning to appear. The concept of preferential flow was to become the "center" of interest in describing soil water movement in the following decade. Another important concept that emerged during the 1980s was the role of the integrated soil–water system in the rapid transport of pollutants from the surface into the underlying groundwater. These interests in integrated systems and preferential water flow were to blossom and provide the basis for describing water and pollutant movement through hydrophobic soil systems in the 1990s. Thus, it seems appropriate to designate this decade as one of "enrichment" in that it was setting the stage for immense progress in understanding water-repellent soil systems in the following decade.

The 1990s started at full acceleration with a workshop, at Wageningen in the Netherlands, on the theoretical and practical dimensions of distribution flow and fingering phenomena. Many of the papers presented at this workshop represented a strong cooperative effort by scientists from the Netherlands and the United States. This workshop set the stage for a full frontal attack on the process of water movement into and through hydrophobic soils by lateral flow on the surface and finger flow through the soil profile. The practical dimension of this effort was the environmental concern with the rapid movement of chemicals and other pollutants through the soils into the underlying groundwater aquifers. Meanwhile, on the other side of the world, in Australia and New Zealand, a strong interest in understanding and ameliorating water repellency was maturing. Two regional conferences in Australia, one in 1990 and a second in 1994, permitted significant discussions of new and innovative techniques for ameliorating water-repellent soils. The treatments to improve water-repellent soils that were discussed at these two conferences include: claying, wide furrowing, use of press wheels, direct seeding, promoting microbial decomposition of hydrophobic substances, and high pH soil treatments.

The remainder of this decade promises to continue to be highly productive, as is indicated by the papers included in this issue. The information presented here is truly a rewarding and significant platform for future endeavors in understanding the role of water repellency in the management of agricultural and wildland environments.

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