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Temporal and spatial soil water management: a case study in the Heilonggang region, PR China

Menggui Jin*, Renquan Zhang, Lianfa Sun, Yunfu Gao

Faculty of Environmental Science and Geotechnique, China University of Geosciences,
Wuhan, Hubei 430074, People's Republic Of China

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Abstract

Long-term over-extraction of groundwater since the 1980s in the Heilonggang region, the East Hebei Plain of North China, has led to serious environmental problems such as seawater or saline water invasion into fresh water, land subsidence, etc. The conflicts between socio-economic development, water shortage and environmental degradation have become increasingly critical. Agriculture, the largest water user in the area and requiring 84% of total water supplied, is creating an unsustainable demand. Soil water is a very important resource in the Heilonggang region as 76% of mean annual precipitation becomes soil water. Effective use of this soil water is, thus, a key for full rational utilisation of water resources in the area. A concept of temporal and spatial management of soil water (TSMSW) is proposed here as a means to ensure effective use of soil water, viz.: management of soil water in full time and possible space dimensions and readjustment of crop distribution in order to harmonise as much as possible crop water demand and soil water availability. Four aspects are included: readjusting crop structures and rotations to fit changes in soil water, increasing the soil water resources, reducing soil water evaporation and managing soil water to meet temporal and spatial crop water demand. Field experiments show that temporal and spatial management of soil water can significantly increase water use efficiency (WUE). For cotton, adopting an integration of micro-topography and plastic mulch has increased WUE from 0.49 to 0.76–0.86 kg/m^3; stalk mulch with manure for winter wheat reached to 2.41 kg/m^3 and straw mulch with deep furrows (micro-topography) for summer maize increased it from 2.06 to 2.34 kg/m^3. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Soil water; Temporal and spatial management; Water use efficiency; Heilonggang, China

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* Corresponding author. Tel.: +86-27-87484610; fax: +86-27-87801763
E-mail address: mgjin@dns.cug.edu.cn (M. Jin)

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1. Introduction

The Heilonggang region is situated in the East Hebei Plain of North China, with an area of 32 966 km^2, 64% of which is cultivated land. Because of a monsoon influence, rainfall is highly variable; mean annual precipitation is 500–600 mm, 80% of which is concentrated between June and September (see Fig. 1). The area is vulnerable, surface water is scarce and shallow saline groundwater occurs widely throughout the area. As a result, natural hazards of spring droughts, autumn floods, soil salinization and alkalization limit agricultural development.

In addition, with the development of agriculture since the 1980s, long-term groundwater over-extraction has led to a reduction of volume in fresh unconfined groundwater and continued lowering of piezometric levels for deep fresh confined water. This has resulted in serious environmental problems such as seawater intrusion, saline water invasion into fresh groundwater, land subsidence, etc. (Zhao et al., 1992; Zhao, 1994). Consequently, the conflicts between socio-economic development, water shortage and environmental degradation become increasingly critical. Agriculture, the largest water user in the area and demanding 84% of total water supply (Zheng, 1992), is facing an unsustainable situation. Obviously water shortage is a bottleneck of the agricultural development in the area.

From the viewpoint of traditional water supply, water resources consist of only surface water and groundwater, the latter being almost the unique water source in the area. Total average available water resources (surface- and groundwater) are 1.869 billion m^3 per year. Averaged for 2 118 000 ha of cultivation land, each hectare can only have 1770 m^3

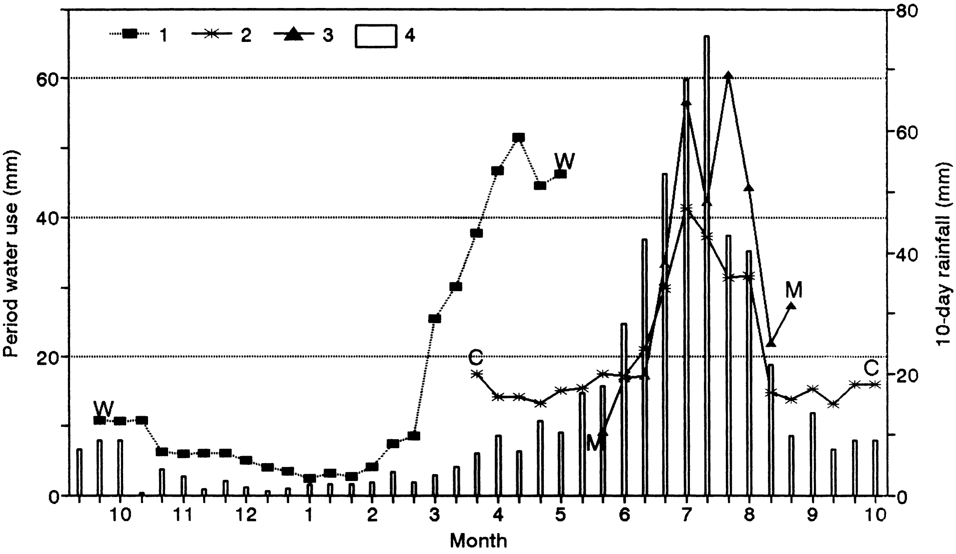

Fig. 1. Comparison of mean crop water use with mean 10-day rainfall (1) winter wheat; (2) cotton; (3) summer maize; (4) 10-day rainfall.

(177 mm) of water. As we know that soil water is the water in the unsaturated root zone and is a pivot (centre) of water cycle between precipitation, surface water and groundwater. From the viewpoint of agriculture (crops), soil water is a principal element of water resources and is a unique form of water which can be utilised directly by crops (Zhang et al., 1994; Jin et al., 1997). Surface- and groundwater can only be used by crops when they transformed into soil water by irrigation or through capillary rise when the water table is shallow. 76% of mean annual precipitation in the Heilonggang region becomes soil water, 15% recharges to groundwater and 9% for runoff (Zhu and Wang, 1993). Effective use of soil water is, therefore, a key for rational utilisation of water resources in the area. A concept of temporal and spatial management of soil water (TSMSW) is, thus, proposed in order to allow effective use of this resource.

2. Relation between crop water requirement and precipitation

In the FAO Irrigation and Drainage Paper No. 24, revised (1977) edition, crop water requirement is defined as: depth of water to meet evapotranspiration of a disease-free crop growing in the large fields without restricting conditions on soil profile, soil moisture and fertility thus achieving full production potential (De Laat, 1985). The main crops in the Heilonggang region are winter wheat, summer maize and cotton. Because of determination difficulty, these crop water requirements are expressed by mean crop water use (actual evapotranspiration) which was evaluated from field experiments in the area. You and Wang (1992), Cheng et al. (1982, 1994) and Ma (1982), respectively, have investigated the water use of winter wheat and summer maize. In order to determine evaporation and transpiration amounts, experiments have been carried out at Wangtong Experiment Station since October 1993. During these, neutron probes and tensiometers monitored soil-water content and matric head. Using observed daily data for soil moisture, matric heads, crop growth, meteorology, etc., daily evaporation and transpiration were calculated using the computer model SWACROP (Belmans et al., 1983; Kabat et al., 1992). Priestley and Taylor equation was used to determine potential evapotranspiration (E^*) and potential soil evaporation ($E_s{}^*$) was derived by the Ritchie equation (Feddes et al., 1978). When rainfall or irrigation exceeds 10 mm, actual evaporation (E_s) is calculated from

$$E_s = 0.35\left(\sqrt{1+0.1n} - \sqrt{0.1n}\right)$$

where n is the number of days after rain or irrigation ($n > 1$).

Fig. 1 summarizes mean 10-day rainfall (averaged from 1972 to 1995) and water use from our experiments and previous researches by other authors (over 10 years). A comparison of average water use and rainfall distribution indicates that the relations between water use and potential water sources are obviously different for winter wheat, summer maize and cotton (Fig. 1). Potential available water sources in the research area are precipitation and soil water only, since there is no groundwater replenishment of the shallow soil storage as water table depth is in the order of 7.8–8.6 m. The precipitation is highly variable in a year and among years, e.g., annual maximum at Wangtong since 1972 was 839 mm (1990) and the minimum was 235.9 mm (1997). 80% of annual rainfall is concentrated between June and September. Growing periods for summer maize, totalling 100–110 days from mid-June to mid/late-September, match the precipitation quite well; total water use is about 300–400 mm, 52% of which (156–208 mm) is transpiration (Ma, 1982; Cheng et al., 1994). Mean precipitation in this period (413 mm, ca. 15–20% percolating to groundwater and no surface runoff in the field) plus usable soil water storage (ca. 210–380 mm) can meet the water demand for summer maize. Hence, with the exception of extremely dry years, summer maize can be rain-fed in the area and generally no irrigation is required.

Cotton growing periods total more than 160 days from mid-April to mid-October and basically coincide with the mean rainfall, though Fig. 1 shows that precipitation between mid-April and late-June is less than the normal water use for cotton. However, since cotton is only a seedling in this period, most of the water use results from soil evaporation and the net water demand for transpiration is only 37–40% on average, or 0.5–1.3 mm per day. This means that cotton can grow on the available soil moisture with little rain in the seedling period, but soil moisture preservative measures are needed for reduction of soil evaporation. Average rainfall in the cotton-growing period is 496 mm and total water use is in the order of 450–750 mm (Cheng et al., 1994). According to field experiments at Wangtong, cotton water use was in the order of 424–518 mm in 1994 and 1995. Cotton can, therefore, be planted in this area relying only on precipitation in a normal year. However, if a dry year is encountered or the rainy season comes too late, irrigation is needed in the second half of June.

In contrast, winter wheat grows in the dry season in the Heilonggang region. Water consumption during the growth period is generally 370–500 mm of water, ca. 60% of which is transpiration (Ma, 1982; Cheng et al., 1994), but average precipitation in the period is only 114 mm and much less in a dry year. The difference between water demand of the wheat and the local precipitation is obviously significant. This means winter wheat has to be irrigated for a certain production. Wheat is very sensitive to water availability during the jointing (elongation)-stage and the milk development period from April to May; potential evaporation and transpiration are highest in the 6-month dry season and natural soil water is sparse. If wheat is not irrigated in time during this period, the crop yield will decrease markedly.

Although water shortage is a bottleneck of the local agricultural development, the agricultural planning in the area is basically based on the demand of population increase and a higher living quality without enough consideration of the local conditions of water resources. According to the above analysis, from the viewpoint of sustainable development, the winter wheat area should be reduced because it requires much more irrigation water than summer maize and cotton. Therefore, agriculture structures need to be adjusted according to the available water resources. The farm practices in the area are extensive with a high irrigation quota, i.e., about 280–350 mm for winter wheat, 120–160 mm for summer maize and 100–210 mm for cotton (Xie and Li, 1991). Experiments in the area have shown that too much irrigation led to a decrease of crop production and water use efficiency and that rational deficient irrigation may result in a higher production and water use efficiency. Thus, the current irrigation quota should be reduced in most areas of the region for the purpose of sustainable development. These need the methodologies of soil water management, water-saving irrigation and the concerning knowledge and techniques for increase of water use efficiency and crop production.

3. A concept of temporal and spatial soil water management and methodologies

Given the framework, that ca. 84% of total water supply is used for irrigation and 76% of annual precipitation remains as soil water, effective use of the latter becomes a key for rational utilisation of water resources in the area. In order to optimally use this soil water, a concept of TSMSW is proposed, viz.: management of soil water in full time and possible spatial dimensions and readjustments of crop distribution in order to harmonise, as much as possible, crop water demand and soil water availability. The concept has four aspects: readjusting crop structures and rotations to fit changes in soil water, increasing the soil water resources, reducing soil water evaporation and managing soil water to meet temporal and spatial crop water demand in the field (Fig. 2).

On a large scale: (1) agriculture and crops are distributed or readjusted temporally and spatially according to prevailing water resources and environmental conditions and (2) new crop types and/or crop rotations which target either water-saving or water-matching or drought-resistant varieties (water matching variety means that this crop water demand regulation is in accordance with local rain distribution and soil water availability).

At a local field scale, soil water is managed by integrating different measures to create optimum micro-hydrologic, meteorological and soil water flow systems in order to

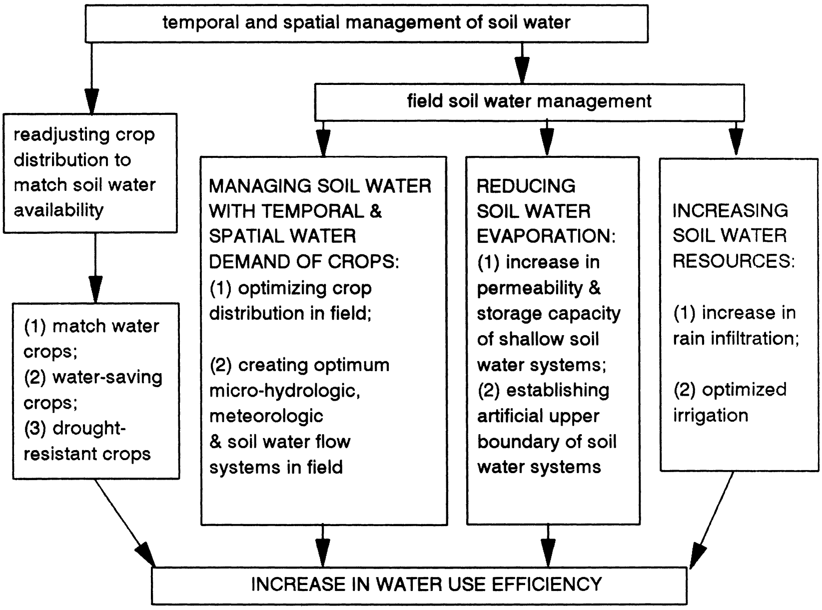

Fig. 2. Summary of temporal and spatial management of soil water.

harmonise crop distributions and soil water in the field, by reducing soil water evaporation, increasing soil water replenishment and hence increasing water use efficiency. Typical measures are:

1. Organic fertiliser, green manure, compost made from stalks, etc. are used to improve soil structure (increase of structural pores). In this manner permeability and storage capacity of shallow soil systems are increased, which in turn increases surface infiltration and decreases soil evaporation and downward leakage of irrigation and rainwater to the deep unsaturated zone or groundwater.
2. The upper boundary characteristics of the soil water flow system are changed by a mulch of stalks or plastic film, loosening the soil, anti-evaporation chemicals, etc. with a view to reducing soil water evaporation.
3. An optimum micro-topography in the field as a result of specific cultivation will create favourable micro-hydrologic, meteorological and soil water flow systems that are of benefit for harmonising soil water distribution and crop water demand. The situation created by a combination of artificial topography and planting pattern concentrates rain or irrigation towards plant roots.
4. Increased irrigation efficiency should be actively encouraged for irrigated field and rain-fed agriculture carefully managed where no irrigation water is applied.

In brief, the TSMSW is a form of systems engineering. Various measures must be combined with crop varieties and rainfall in their growing season, with a careful analysis of site-specific problems in order to arrive at reasonable rational solution. For example, soil moisture preservation measures may be adopted in the dry season or in fallow fields; soil water management in any period should take account of the soil water distribution and spatial differences in water uptake by roots, concentrating water to the root zone or densest root area; crops should first be sown in areas with adequate natural soil water.

4. Field experiments for temporal and spatial management of soil water

Based on the methodologies of TSMSW mentioned above, field experiments for winter wheat, cotton and summer maize were carried out at Wangtong Experiment Station in the past years. Some of these experiments are reported in this section. A meteorological station was set up at the centre of the experimental station to collect daily meteorological data, including precipitation, evaporation, temperature of air and soil, humidity, wind, sun-shining hours, etc. The unsaturated zone profile in the experimental fields is made up as follows:

0–1.25 m:	sandy loam
1.25–2.10 m:	silt
2.10–3.55 m:	clay
3.55–4.10 m:	sandy clay loam
4.10–4.90 m:	silt
4.90–5.10 m:	clay
5.10–5.70 m:	silt

Soil of cultivated-layer (top 30 cm) in the experimental field is yellowish-brown sandy loam, pH = 7.6–8.0, with nutrients:

total-nitrogen,	0.060–0.062%
available nitrogen,	38.9–41.2 ppm
available phosphorus,	3.8–6.1 ppm
available potassium,	94.0–104.0 ppm
organic matter,	0.77–0.91%.

4.1. Field experiments for cotton

4.1.1. Experimental schemes

The seedling period of cotton is generally from mid-April to mid-June, in a period with little rain. Measures to preserve moisture and efficient irrigation are, therefore, desirable. Since most water loss in cotton fields during the seedling period is soil evaporation, plastic covers are a simple way for reducing evaporation and in combination with early sowing to increase soil temperature. Fig. 3 shows the different planting schemes adopted for the cotton experiments.

J_3^1 – normal planting scheme with no covering plastic film.

K_1 – cotton is planted in furrows with a full cover of plastic film and holes only for seedlings. This results in: (1) a small amount of rain (between May and June) is concentrated and infiltrates into the root area through the seedling holes, hence,

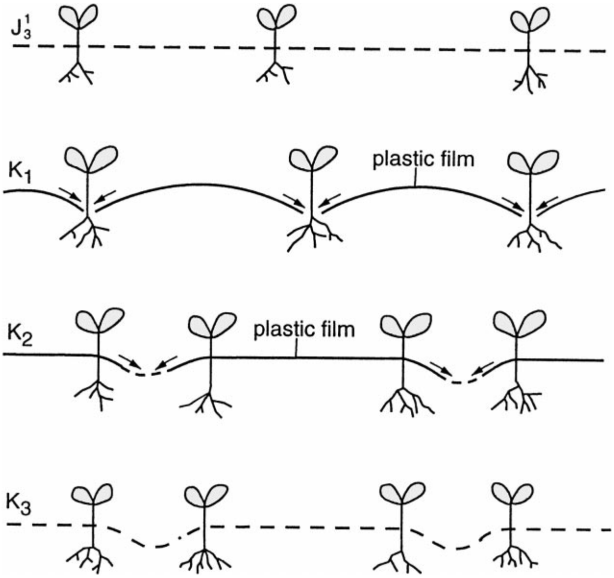

Fig. 3. Illustration of the different planting schemes.

transforming minimum input into heavy rain for the young cotton; (2) during irrigation, water infiltrates only into the root area through the seedling holes, thus, minimising the necessary application; (3) fully covering with plastic film greatly reduces soil surface evaporation during the early period with a low vegetation cover; (4) salt accumulation in the root zone is prevented when irrigating with brackish water; and (5) salt can be easily flushed by this concentrated infiltration while irrigating or during rain.

K_2 – cotton is planted on ridges covered with plastic film but with a gap in the furrows. This has the same effect as for K_1 in that irrigation or rainwater is concentrated to infiltrate only in the root area and soil surface evaporation is greatly reduced.

K_3 – the planting scheme is the same as for K_2, but without a plastic film cover.

Taking experiments of 1994 for example, the cotton was sown in early-May and harvested in mid-October. Precipitation in the growing period of the cotton was 460 mm (Fig. 4), but only 19 mm for the first 50 days (before irrigation on 22 June). Three neutron tubes (200 cm in depth) were located in distances of 15, 30 and 45 cm to cotton for soil moisture observation on treatment K_1 and K_2 by neutron probes, and the rest were located 30 cm away from cotton. Measurements were normally made every 3–5 days, but once a day after rain or irrigation. Since the in situ measurement of neutron probes for topsoil is not stable due to changes of up boundary condition with crop growing, an oven-dried method in a laboratory was also used to determine soil moisture at depths of 10 and 20 cm. The soil samples for oven-dried method were sampled two times a month at alternative points, which results were used to verify that of neutron probes.

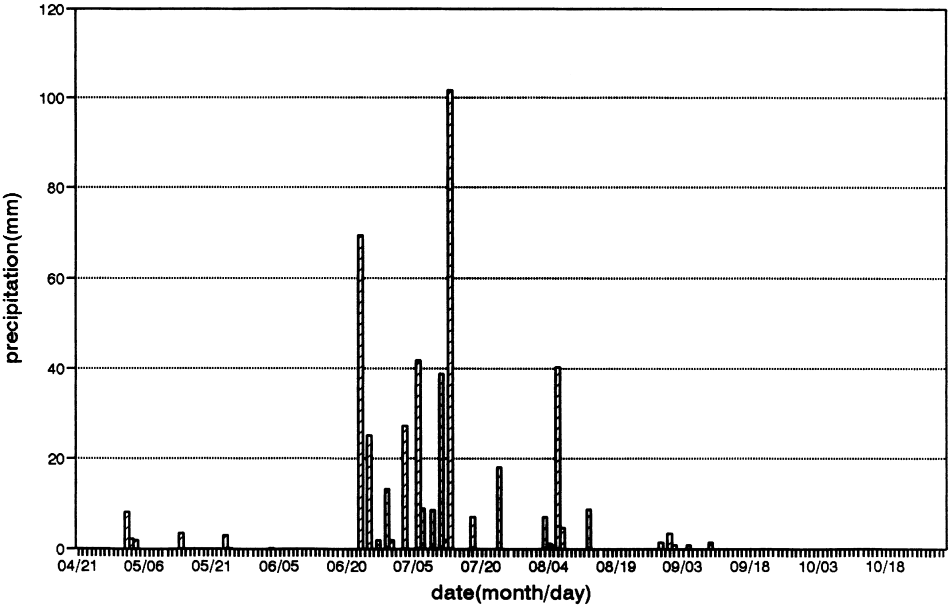

Fig. 4. Precipitation in the cotton growing period for 1994 at Wangtong.

4.1.2. Results and discussions

The experimental results are summarised in Table 1 through Table 5. They indicated that treatment integrating artificial micro-topography and plastic mulch such as K_1 and K_2 gave much higher output and conserved more water in comparison with the normal planting scheme $J_3{}^1$ (see Table 1). For example, K_2 uses 30 mm less irrigation water for a yield, which is 30% higher than for $J_3{}^1$. Measured soil moisture data for K_1 and K_2 after irrigation with brackish water (3.5 g/l of TDS) on 22 June show that moisture levels near the cotton are higher than the surrounding area (23 June, Tables 2 and 3); infiltrated water has remained near the cotton roots, thus greatly increasing water use efficiency.

Table 1
Comparison of different cotton planting scenarios (1994)

Treatment No. (see Fig. 3)	Irrigation application (22 June) (mm)	Sown date	Emergence date	Unginned cotton output (kg/ha)	Ginned cotton output (kg/ha)	Water use efficiency (kg/m^3)
K_1	15	01/05	08/05	1556	3661	0.86
K_2	30	01/05	13/05	1387	3265	0.77
K_3	30	01/05	18/05	1376	3237	0.76
J_3^1	60	05/05	13/05	967	2417	0.49

Table 2
Soil moisture (vol.%) for different distances to individual cotton stems (K_1)

Date	05/06/94			23/06/94		
Distance (cm)	10	30	45	10	30	45
Depth (cm)						
10	9.4	16.1	17.0	14.5	12.3	10.8
20	20.9	22.3	22.8	21.4	17.7	16.2
30	24.8	24.8	24.3	22.6	20.3	19.5
60	25.7	25.2	25.4	24.1	23.4	23.4
100	32.0	31.4	31.4	31.5	31.4	31.3
150	38.7	38.8	38.8	38.5	39.2	38.1
200	41.8	41.2	40.4	42.4	40.6	40.9

Table 3
Soil moisture (vol.%) for different distances to individual cotton stems (K_2)

Date	05/06/94			23/06/94		
Distance (cm)	10	30	45	10	30	45
Depth (cm)						
10	14.4	13.2	15.7	15.3	11.6	11.3
20	22.7	22.1	23.3	20.0	16.1	16.8
30	23.3	22.6	23.8	20.5	17.7	18.9
60	25.9	23.0	24.6	23.1	22.1	23.8
100	31.9	30.9	32.2	31.0	30.2	31.7
150	40.2	39.9	41.3	40.7	39.2	40.6
200	43.1	42.8	42.9	44.2	42.2	42.3

Table 4
Profiles of soil moisture (vol.%) at 30 cm distance to cotton for K_1, K_2, K_3

Date Depth (cm)	05/06/94			20/06/94			23/06/94		
	K_1	K_2	K_3	K_1	K_2	K_3	K_1	K_2	K_3
10	16.1	13.2	12.2	10.2	9.2	8.8	12.3	11.6	9.3
20	22.3	22.1	20.9	16.8	16.6	15.2	17.7	16.1	19.5
30	24.8	22.6	22.6	20.3	19.8	17.5	20.3	17.7	19.7
60	25.2	23.0	23.1	23.7	22.3	21.4	23.4	22.1	22.0
100	31.4	30.9	30.5	31.3	30.3	30.1	31.4	30.2	29.8
150	38.8	39.9	40.2	38.8	39.5	38.5	39.2	39.2	39.4
200	41.2	42.7	42.0	41.1	41.5	41.5	40.6	42.2	41.1
Soil water storage (mm)	622	613	608	593	585	570	597	583.9	583.8

Note: soil water storage is the water volume (in mm) stored in a 2 m soil column.

Under conditions of evapotranspiration without infiltration (5 June, Tables 2 and 3), the water content around cotton roots for K_1 and K_2 is lower because the sink term is only transpiration (evaporation is prevented by the plastic film). Background of soil moistures before sowing (1 May) are almost the same, but there are significant differences for K_1, K_2 and K_3 1 month later (5 June, Table 4). Although the plant height and leaf area index for K_3 are less, soil water consumption is greater than that for K_1 and K_2; residual soil water for K_3 is thus less than that for K_1 and K_2. Changes in soil water storage from 5 June to 20 June further indicate that evaporation from the soil surface at K_3 is greater than that for K_1 and K_2.

The same experiments have been repeated after 1994 but no irrigation was applied after sowing. Average production for different scenarios were summarised in Table 5.

Table 5
Water use efficiency of cotton in Wangtong experimental station

Treatment	Year	Rainfall (mm)	Irrigation (mm)	Deep percolation (mm)	Changes of soil water storage in top 2 m	Water use (mm)	Ginned cotton output (kg/ha)	Water use efficiency (kg/m^3)
K_1	1994	459.9	15	92	−40.7	423.6	3661	0.86
K_2	1994	459.9	30	92	−28.2	426.1	3265	0.77
K_3	1994	459.9	30	92	−30.1	428.0	3237	0.76
J_3^1	1994	459.9	60	92	−61.3	489.2	2417	0.49
J_2	1994	459.9	60	92	−94.7	522.6	2708	0.52
K_1	1995	635.7	0	127.4	+1.6	507.0	1663	0.32
K_4	1995	635.7	0	127.4	+6.6	501.9	1224	0.24
K_2	1995	635.7	0	127.4	+2.4	506.2	1708	0.34
K_3	1995	635.7	0	127.4	−9.0	517.6	1523	0.29
K_1	1997	174.7	0	0	−41.98	216.7	4151	1.91
J_2	1997	174.7	0	0	−124.2	358.9	3583	1.19
J_3^1	1997	174.7	0	0	no data		3789	

Note: J_2 – flat topography partly cover with plastic; K_4 – same topography as K_1 without mulch; irrigation-excluding 45–60 mm of water irrigated before sowing.

The results indicated further that scheme K_1 is special good against dry but not for a wet year. 1995 was a wet year (annual precipitation was 653.2 mm) and especially an unbroken spell of wet in the periods of cotton buds and bolls so that production for that year was very low. Therefore, we have proposed an improvement on K_1, i.e., cotton is planted in furrows before late-June, after that change the field-micro-topography to make cotton on ridges. K_2 seems more feasible than K_1 for a wet year. Production and water use efficiency for those treatments using plastic mulch were relatively higher. Cotton production and water use efficiency dominated by many factors such as weather, soil moisture, fertiliser, injurious insect, field management, etc. Only a good combination of these factors can obtain a high production but any of these may result in a low production. Production and water use efficiency for K_1 in 1997, an extremely dry year with precipitation of 235.9 mm, were the highest (4151 kg/ha, 1.91 kg/m^3) in the experimental years.

4.2. Field experiments for winter wheat

As mentioned earlier, application of organic fertiliser may increase permeability and porosity or storage capacity of shallow soil systems and mulch with crop straw can change the upper boundary conditions of soil water flow systems. These two ways were combined to increase water use efficiency for winter wheat of 1995–1996 at Wangtong Experiment station (see Table 6). Soil moisture was measured by neutron probe, and each treatment had one observation tube. Measurement frequency was the same as cotton. By comparing different wheat treatments for the period 1995–1996, the water use efficiency of 95–96E_1 (straw mulch with manure) 2.41 kg/m^3 was the highest. But it seems difficult to explain the order of production.

Table 6
Experiments on soil water management for winter wheat

Number	Treatment	Precipitation (mm)	Irrigation (mm)	Average production (kg/ha)	Water use (mm)	Water use efficiency (kg/m^3)
93–94a	organic fertiliser (soya-bean cake, 2025 kg/ha)	129.7	37.5 × 2	5187	261.6	1.98
93–94b	no organic fertiliser	129.7	37.5 × 2	3872	259.7	1.49
94–95a	straw mulch (4500 kg/ha)	148.3	45 × 2	7150	268.1	2.67
94–95b	no mulch	148.3	45 × 2	6800	295.4	2.30
95–96E_1	straw mulch (4500 kg/ha) and manure (45 000 kg/ha)	69.3	45 × 2	5707	236.4	2.41
95–96E_2	straw mulch (4500 kg/ha) with no manure	69.3	45 × 2	5857	260.4	2.25
95–96E_3	no mulch and no manure	69.3	45 × 2	5598	249.2	2.25
95–96E_4	manure (1 35 000 kg/ha) and straw mulch (4500 kg/ha)	69.3	45 × 2	5225	234.5	2.23
95–96E_5	manure (1 35 000 kg/ha) with no mulch	69.3	45 × 2	4953	242.6	2.04

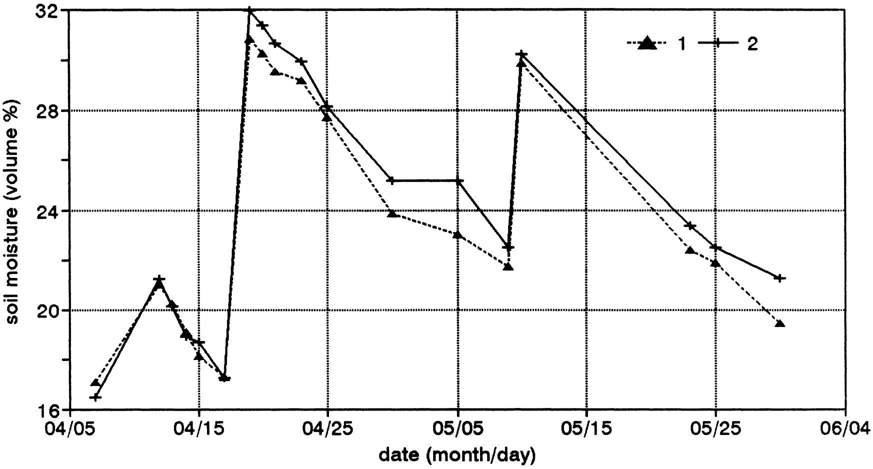

Fig. 5. Comparison of soil moisture at 30cm depth with and without application of organic fertiliser; (1) no application of organic fertiliser (93–94b); (2) application of soya-bean cake of 2025 kg/ha (93–94a).

The effect of organic fertiliser was tested for winter wheat 1993–1994 (93–94 in Table 6). This wheat was sown on 2 October 1993, irrigated by 45 mm of water (2.9 g/l in TDS), respectively, on 18 April and 9 May 1994 and harvested on 3 June. Rainfall in the growth period was 127.9 mm. Water use efficiency for application of organic fertiliser was 1.98 and 1.49 kg/m^3 for no application of organic fertiliser. The former production was 33.9% higher than the latter. Nutrients derived from the organic fertiliser was really helpful for the increase of wheat production, and an investigation of soil moisture indicated that soil moisture of 93–94a (applying organic fertiliser) was higher than 93–94b (Fig. 5).

From Table 6, one can see that the production of winter wheat 94–95 with stalk mulch was 5.1% higher than no mulch; and the former water use efficiency was 16% higher than the latter. But the wheat was ripe 3 days later. The differences of soil moisture for these two treatments are shown in Fig. 6. Field observation indicated that soil temperature of the former was higher than the latter before April, but inverse after April, maximum difference being 3.1°C (Table 7). Therefore, straw mulch can not only change soil water

Table 7
Soil temperature (°C) at 5 cm depth for winter wheat of 1994–1995 with and without mulch

	Date	12/11	12/12	12/13	12/14	12/15	03/22	03/23	03/24	05/03	05/04	05/05
94–95a	8 : 00	3.8	2.5	1.8	1.0	0.5	6.5	5.5	4.5	11.0	12.0	13.0
	14 : 00	4.5	4.0	3.4	2.5	0.5	10.5	8.5	11.5	17.5	18.5	21.0
	20 : 00	3.7	3.0	2.5	1.4	0.4	8.5	6.5	8.5	15.0	16.0	19.0
	Average	4.0	3.2	2.6	1.6	0.5	8.5	6.8	8.2	14.5	15.5	17.7
	8 : 00	2.5	1.2	0.4	−0.2	−1.5	6.0	5.0	4.0	10.0	12.0	13.7
94-95b	14 : 00	4.8	5.0	1.7	0.0	−0.3	12.5	9.5	12.0	21.0	23.0	25.7
	20 : 00	2.0	2.0	1.2	−0.1	−0.5	8.0	6.0	8.0	17.5	20.0	23.0
	Average	3.1	2.7	1.1	−0.1	−0.8	8.8	6.8	8.0	16.2	18.3	20.8

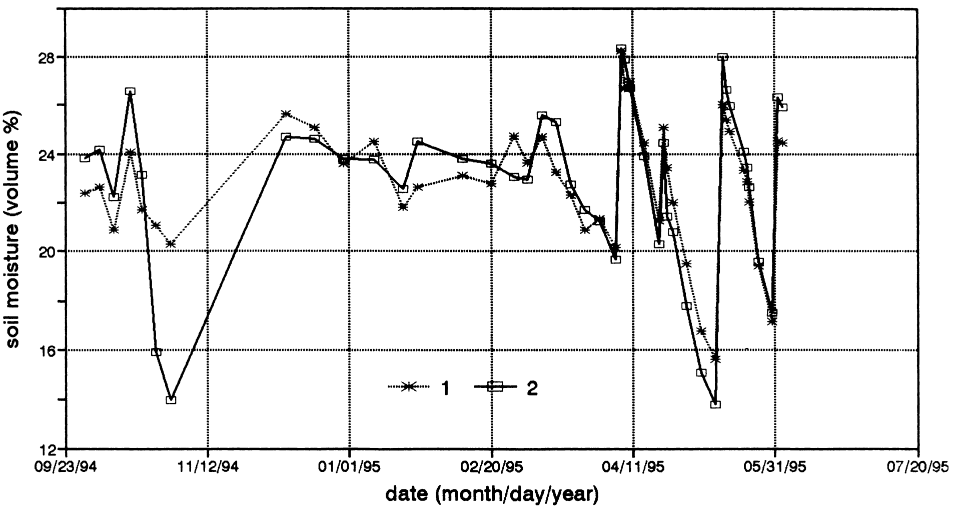

Fig. 6. Comparison of soil moisture at 20cm depth with and without straw mulch; 1- mulch with wheat straw (94–95E$_1$); 2- no mulch (94–95E$_2$).

movement but also thermal and solute transport to form a better soil water flow systems for crop to increase production and water use efficiency. However, lower soil temperature caused by straw mulch led to late maturing of wheat for several days because low temperature is not good for wheat to turn green in March.

4.3. Field experiments for summer maize

Precipitation in a normal year can generally meet water requirement of summer maize in the area, but problems remain dry in early stage (June) and waterlogging in the late period (mainly in August). Our integrated strategy against these two was: straw mulch with deep furrows (micro-topography) which can form favourable micro-hydrologic, meteorological and soil water flow systems that are of benefit for harmonising soil water distribution and crop water demand. This straw mulch decreases soil evaporation while

Table 8
Experiments on soil water management for summer maize of 1996

Number	Treatment	Precipitation (mm)	irrigation (mm)	Average production (kg/ha)	Water use (mm)	Water use efficiency (kg/m^3)
96E$_1$	straw mulch (4500 kg/ha) with deep furrows	429.6	0	7567	319.0	2.34
96E$_2$	deep furrows with no mulch	429.6	0	6750	304.5	2.15
96E$_3$	no furrows with straw mulch (4500 kg/ha)	429.6	0	7025	315.8	2.22
96E$_5$	no furrows and no mulch	429.6	0	6200	301.2	2.06

soil cover in the seedling stage is low and the deep furrow drainage against water-logging during rain season. The experimental results of 1996 are shown in Table 8. The maize was sown on 7 June, emerged on 11 June and was ripped on 15 September. Sixty mm water was irrigated before sowing and rainfall within the growing period was 430 mm (a normal year of rainfall). Production and water use efficiency for the integrated way ($96E_1$) was significantly higher than the others; and the traditional one ($96E_5$) was the lowest. However, this strongly needs further experiments.

5. Conclusions

Temporal and spatial management of soil water is a form of systems engineering. It is concluded that a good combination of different measures in the field can form favourable micro-hydrologic, meteorological and soil water flow systems for harmonising soil water distribution and crop water demand and significantly increase water use efficiency. The field experiments show that integration of micro-topography and plastic mulch (such as K_1 or K_2) is a good way to increase water use efficiency and production of cotton; stalk mulch with manure is suitable and feasible for winter wheat; straw mulch with deep furrows (micro-topography) seems a good way for summer maize under the given conditions. However, the concept of TSMSW needs further experiments to prove the feasibility of the practical schemes and to create better-operational measures. If the proposed strategies of soil water management could be practised in half of the whole Heilonggang region and assume each hectare irrigation land (52% of total cultivated land) save at least 600 m^3 water, 660.8 million m^3 water will be saved each year for a similar production even a high. In addition to readjust the agriculture structures on the basis of available water resources, the agricultural development in the area will be sustainable.

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