Water-Saving Agriculture and Sustainable Use of Water and Land Resources

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Foreword

Shortage of water resources and deterioration in the quality and availability of agricultural land are worldwide problems. Water and land are critical resources and cannot be regarded as available in abundance. Degradation of land, reduction of river flow and the increasing frequency of severe dust storms have seriously damaged the natural environment and retarded economic development. These problems have reached dangerous levels in many countries. It is widely believed that an increase the efficiency with which water is used in agriculture is one key way to reduce many of these problems. For many countries, agriculture is the largest water user and to improve water use efficiency in agriculture would have a significant impact on sustainable development. It is not only important to ensure availability of water in the right quantity at the right time, but also important to ensure that water of an appropriate quality is used in agriculture. Therefore, research on water efficient agriculture, and on sustainable use of water and land resources in arid and semiarid areas has a high international priority.

Water shortage in China, particularly in Northwest China is very serious. This region (including Shaanxi, Gansu, Ningxia, Qinghai, Xingjiang and Western Inner Mongolia) accounts for 1/3 of the area of China, but has only 8.3% of total national available water resources. While the water shortage in this region is serious, the waste of water resources and water pollution remain as major issues. Overall irrigation water use efficiency is approximately 40%, with atypical irrigation water productivity around 0.46 kg/m$^3$. Excessive irrigation in Ningxia and Inner Mongolia have had a significant influence on Yellow River downstream water users. The frequency and severity of dust storms, sourced from the Northwestern China, have been increased every year. This is accompanied by an increase in the desertification of large areas of land.

The importance of water-saving agriculture and sustainable use of water and land resources are increasingly being recognized by public and government authorities. To address many of the important issues raised above, the “International Conference on Water-saving Agriculture and Sustainable Use of Water and Land Resources” (ICWSAWLR) will be held on October 26-29, 2003 in Yangling, Shaanxi Province of P.R. China, which organized by Northwest Sci-Tech University of Agriculture and Forestry (NWSUAF) of China and the Lancaster Environment Center, Lancaster University (LEC) of UK, and sponsored by NWSUAF, the Journal of Experimental Botany (JXB), National Natural Science Foundation of China (NSFC), Chinese Hydraulic Engineering Society (CHES), Chinese Society of Agricultural Engineering (CSAE), the Key Lab of Agricultural Soil and Water Engineering in Arid and Semiarid Areas of Ministry of Education of China (LASWE), Center of Agricultural Water Research in China (CAWR) of China Agricultural University.

The objectives of the conference are to bring together a multi-disciplinary group of researchers, engineers and regulators to present and discuss current research. The conference themes include biological mechanisms of water-saving agriculture, agronomic technology and
plant improvement for water-saving in water-limited areas and dryland, irrigation technology and water management, sustainable use of water resources in arid and semiarid areas, agricultural water and land environment. The secretariat received more than 240 abstracts, all of them were edited, they and with the selected some full papers will be published in the special issue of Journal of Experimental Botany, and the other full papers, which the secretariat received, are published in this proceedings. We thank Du Taisheng, Martin Parkes, Jeff Gale, Rupert Knowles, Rachel Caiger, Wang Zhinong, Hu Xiaotao, Ma Xiaoyi and the anonymous reviewers who helped in checking papers and in preparing the conference.

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Section II

Agronomic Technology and Plant Improvement for Water-Saving
Theory and methods of drought system analysis

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Abstract
Drought duration and severity were studied, based on analysis of statistical parameters including mean, coefficient of variation and serial correlation of drought phenomena. Extreme drought duration and severity expressions were developed. Taking Dongzhou Reservoir as an example, the related design parameters were calculated.

Key words: Drought frequency; drought duration; drought severity; truncated level.

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1 Introduction
Droughts have currently attracted much attention in different areas. The sequences of rainfall or stream flow that are used to characterize droughts are known as drought variables. In general, droughts are measured in terms of deficiency of rainfall or stream flow below a predefined reference level. The cumulative deficit during a drought spell is known as the severity, measured either in mm or m$^3$. For identification of droughts or for quantifying severity, the reference level is termed the truncation level. It is taken to be equal to the long-term mean of the drought variable sequence.

To create provisions for meeting the exigencies during a drought spell, the most important parameters are the longest duration and the largest severity for a desired return period of T years. These are identified as extreme duration and severity in this paper. The drought sequence could be distributed normally or may have a skewed distribution. The simple types of probability density functions (pdfs) used for modeling annual rainfall and runoff sequences are normal, log-normal and gamma, all with two parameters. Likewise, the simplest kind of dependence is Markovian, represented by the lag-one serial correlation coefficient $\rho$. For a given place or basin, the reliable statistics available for annual rainfall and stream flow are the mean, coefficient of variation and lag-one serial correlation coefficient. One might wish to ask the following questions based on these values. (1) How does the coefficient of variation, skewness and dependence affect the extreme duration and severity characteristics? (2) Is there any formula in terms of the largest severity and return period that parallels the flood frequency formula, commonly cited in the hydrological texts? This flood frequency formula is used for design of runoff handling structures. A drought frequency formula could be used for design of water storage structures to cover drought periods. So statistical theory was applied to answering these questions.

2 Stochastic analyses of extreme drought duration and severity
2.1 Evaluation of drought probability quantile $q$
If a time-series $x_i$ of modular form, with mean ($\mu_x$) and standard deviation ($\sigma$) is truncated at the mean level $= 1$, then the occurrence of excesses ($x_i < x_m$) and deficits ($x_i > x_m$) appears along the time axis. The truncation level can be assigned a probability quantile $q = P(x_i \leq x_m = 1)$, where $q$ is the probability of drought corresponding to the truncation level $x_m = 1$ and $P(\ldots)$ represents probability.

For a normal pdf, the relationship between $q$ and the truncation level can be obtained by standardizing the sequence $x_i$ into $z_i$, where $z_i$ has mean $= 0$, $\sigma = 1$ and a standard normal distribution. Thus, for a normal pdf, with coefficient of skewness ($C_s$) = 0, the value of $z_i$ corresponding to $x_m= 1$ is 0. Hence $q = p(x_i \leq 1) = P(z_i \leq 0) = 0.5$ is easily obtained from standard normal probability tables or through the following standard normal probability integral

$$ q = \int_{-\infty}^{z} \frac{1}{\sqrt{2\pi}} \exp(-0.5z^2)dz \quad (1) $$

The value of $z_i$ corresponding to $x_m = 1$ for a normal pdf has the value 0 and is identified as $z_m$ in the text. An $x_i$ sequence can also be standardized as $u_i = 2x_i / x_m - 1$, where the $U_i$
sequence has mean = 0 and standard deviation = 1. Therefore \( x_i \) can be expressed in terms of mean \( (x_m) \) and coefficient of variation \( (C_v) \) as follows

\[
x_i = x_m \frac{\hat{h}}{C_v} + u_i \tag{2}
\]

For a log-normal distribution, the value of the truncation level \( z_{ml} \), equivalent to the mean of a sequence \( x_m = 1 \), can be worked out using the following explanation. If \( x_i \) is a log-normal variate with a mean \( x_m \), standard deviation \( \hat{\sigma} \) and coefficient of variation \( (C_v) \) then \( \ln(x_i) \) is normal with a mean \( \frac{\hat{\sigma}}{C_v} \) and standard deviation \( \frac{\hat{\sigma}}{C_v} \). As with \( x_i \), the variate \( \ln(x_i) \) can also be standardized and the new normal standardized variate designated as \( z_i \) can be expressed as

\[
z_i = \frac{\ln(x_i) - \frac{\hat{\sigma}}{C_v}}{\frac{\hat{\sigma}}{C_v}} \tag{3}
\]

Since \( u_i = 0 \) at the mean level of an \( x_i \) sequence, so the corresponding value of \( z_i \) can be expressed using Equation (3) as

\[
z_{ml} = \frac{\ln(x_m) - \frac{\hat{\sigma}}{C_v}}{\frac{\hat{\sigma}}{C_v}} \tag{4}
\]

The moments of \( x_i \) and \( \ln(x_i) \) are related by the following relationships

\[
? ? \ln( x ) = 0.5 ? \tag{5}
\]

\[
? ? \ln( 1 + C ) \tag{6}
\]

So, using Equations (5) and (6), Equation (4) can be simplified as

\[
z_{ml} = \frac{\ln(x_m) - 0.5? \ln(1 + C_v^2)}{\frac{\hat{\sigma}}{C_v}} \tag{7}
\]

Note the modular form, hence \( x_m = 1 \) in all the above relationships. Since \( z_{ml} \) is a standard normal variate, hence the value of the probability quantile of the equation \( q \) is \( P( z_i < z_{ml} ) \) can be obtained from the standard normal probability tables or can be computed by numerical integration of the standard normal function shown in Equation (1), with \( z_m \) replaced by \( z_{ml} \). Looking at the structure of Equation (7), it is evident that \( z_{ml} \) is greater than 0 for the mean of the \( x_i \) sequence, when \( x_m = 1 \). Hence the value of \( q \) for a log-normally distributed sequence will always be greater than 0.5 and is dependent on the \( C_v \) of the sequence. The effect of skewness is implicitly included in \( C_v \) since, for a log-normal pdf, \( C_v \) and \( C_s \) are functionally related through the following relationship

\[
C_s = 3 C_v \tag{8}
\]

The same analysis can be extended to the two-parameter gamma distribution. If \( ? i \) is the standardized gamma variate \( ? i = (x_i - 1)/C_v \), then the standardized normal variate \( z_i \) is approximately related to \( ? i \) through the following relationship

\[
z_i = \frac{6}{C_v} \ln(C_s ? i ? 1)^{0.666} - 1 \tag{9}
\]

For a two-parameter gamma variable \( C_s > 2 C_v \), hence Equation (9) can be reduced to

\[
z = 3 C \ln ? i ? 1^{0.666} 0.333 C \tag{10}
\]

Therefore, a modular gamma variate can be transformed into a standard normal variate using Equation (10) and at the mean level, \( x_m = 1 \), \( z \approx 0.333 C \). Note the value of \( z_i \) is designated as \( z_{ml} ? \) for \( x_i = 1 \). That is, if the drought variable is gamma distributed then, at the truncation level equal to the mean of the sequence, the equivalent standard normal variates \( z_{ml} ? \) will be 0.0666, 0.1332, 0.2098, 0.2664 and 0.333 for \( C_v \) values of 0.2, 0.4, 0.6, 0.8 and 1, respectively. For a normally distributed drought variable they will all be equal to 0, regardless of the \( C_v \). So the probability quantile for a gamma-distributed drought variable could be worked out for the desired value of \( C_v \) by consulting standard normal probability tables or through integration of Equation (1), replacing \( z_m \) by \( z_{ml} ? \). Note here again that \( z_{ml} ? > 0 \) for \( x_m = 1 \). For example, a gamma-distributed drought variable with \( C_v = 0.4 \) and \( z_{ml} ? = 0.13 \) has \( q = 0.55 \) at the level of truncation equal to the mean sequence level, as compared with 0.5 for a normally distributed drought variable or 0.58 for a log-normally distributed variable. Table 1 gives values of \( q \) for normal, two-parameter gamma and log-normal pdfs, for various \( C_v \) values.

2.2 Modeling extreme drought duration

Any uninterrupted sequence of deficits can be regarded as a drought length (duration) equal to the number of deficits in the sequence, designated by L (\( L = 1, 2, 3, ..., j \)). Each drought duration is associated with deficit sum D, being the sum of individual deficits, \( d_1, d_2, d_3, ..., \) in successive epochs of the spell. This deficit sum is termed the drought standardized sequence of the drought variable. The actual severity (D) is functionally related to a standardized severity (S) through the relationship \( D \approx S \) (Guven, 1983). The term S/L is termed the drought intensity or magnitude. One can expect \( n = 0, 1, 2, 3, ..., i \) drought spells, or runs, over a period of \( T \) years and correspondingly there will be \( n \) values of severities designated as \( D_1, D_2, D_3, ..., S_1, S_2, S_3, ..., \) in standardized terms.
A designer is interested in the longest values of \( L \), designated as \( L_T \), and the largest value of \( S \), designated as \( S_T \). The period ‘\( T \)’ means a sample size of \( T = 10, 20, \ldots, 100 \) years and can be regarded as equivalent to a return period of \( T \) years. The probabilistic relationship for \( L_T \) can be obtained by applying the theorem of extreme of random number of random variables. The computations for drought durations and severities are greatly simplified if the analysis can be carried out in the standardized form. The analysis in this form does not affect magnitude of the duration \( (L) \) but does affect the magnitude of severity \( (D) \). The mean has no effect on severity as it is the difference between magnitude of the drought variable and the mean itself. So, in the course of mathematical derivations for severity, the mean cancels out, leaving standardized severity, which can be transformed into actual severity \( D \) by the above relationship. The following relationships can therefore be deduced for \( L_T \) following the work of Guven (1983).

\[
P(L_T > j) = \left( \frac{1}{2} \right) \frac{\exp \left(-2q \sqrt{j} \right)}{q \sqrt{j}} \text{ for } j = 0, 1, 2, \ldots, n
\]

where \( q \) is the probability quantile defined earlier and \( r \) is conditional probability of any year being a drought year, given that the past year is also a drought year. Substituting Equations (12) and (13) into Equation (11) and simplifying, gives the following relationship

\[
P(L > j) = \exp \left(-q T (1 + r)^{\frac{1}{2}}\right) P(L_T > j)
\]

The expected value of \( L_T \) can be obtained by using the formula

\[
E(L_T) = \left( \frac{j}{j+1} \right) p(L_T > j)
\]

Since \( p(L_T > j) \) = \( P(L_T > j + 1) \) = \( P(L_T > 1) \), so an expression can be derived for \( p(L_T = j) \) from Equations (13) and (14), giving

\[
p(L_T > j) = \exp \left(-q T (1 + r)^{\frac{1}{2}}\right) P(L_T > j)
\]

Conditional probability, \( r \), is related to the lag-one serial correlation coefficient \( \beta \), through the following equation.

\[
r = q \left( \frac{1}{2} \right) \frac{\exp \left(-0.5 Z (1 + ?) \right)}{Z (1 + ?)}
\]

where \( ? \) is the lag-one serial correlation coefficient of the Markov process and \( Z \) is a dummy integration variable. Equation (17) can be determined by a numerical integration procedure. So values of \( r \) can be computed for given \( ? \) at the truncation level, where \( z_0 = z_m \) for a normal pdf, \( Z \) for a gamma pdf and \( z_0 = z_m \) for a log-normal pdf. It is evident from Equation (17) that for independent processes \( r = q \). It should be noted that if a \( x_i \) sequence is normal, \( ? \) can be substituted as it is, but for a log-normal pdf

<table>
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<tr>
<th>Model</th>
<th>Distribution</th>
<th>( n )</th>
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Table 1 Values of \( q \) and \( r \) at the mean level for different probability distributions
should be converted to $Z_1$. This is the right value in the normalized domain and $Z_0 \neq Z_{nl}$. The relationship between $Z_1$ and $Z_0$ is of the following form

$$Z_1 = \frac{\ln\left(\frac{\gamma^2 C_V^2}{\ln(1 + C_V^2)}\right)}{\ln(1 + C_V^2)} \quad (18)$$

For a gamma pdf, $Z$ remains unchanged but $Z$ replaces $Z_0$. Values of $q$ and $r$ for various pdfs, $C$ and $Z$ values are shown in Table 1. It is evident from Table 1 that, for a normal pdf, $q$ is constant equal to 0.5 regardless of the coefficient of variation. While for a log-normal pdf, it is dependent on $C$ and in turn on $C_v$. Values of $r$ are dependent on $q$ for a normal pdf and on $C$ and $C_v$ for gamma and log-normal pdfs. In all cases, a log-normal distribution tends to have a greater value of $q$ and $r$ for identical values of $C_v$ and $C$. Values of $q$, $r$, and $Z$ differ by the coefficient of variation. Thus, for a normal pdf, $q$ is constant equal to 0.5. For a log-normal pdf, it is dependent on $C_v$ and in turn on $C$. Values of $r$ are dependent on $q$ for a normal pdf and on $C$ and $C_v$ for gamma and log-normal pdfs. In all cases, a log-normal distribution tends to have a greater value of $q$ and $r$ for identical values of $C_v$ and $C$.

2.3 Modeling Extreme Drought Severities

A probabilistic relationship for $S_T$ can be obtained in parallel to Equation (11), derived for $L_T$.

$$P(S \leq Y) \sim \frac{p(n = 0)\cdot P(S = Y)\cdot p(n = i)}{1} \quad (19)$$

where $Y$ can take values such as 0, 0.1, 0.2, ..., 60. These values are dimensionless and 60 represents an extremely large value. Substituting the expression for $p(n = i)$ from Equation (12) into Equation (19), the result is

$$P(S \leq Y) \sim \exp(\gamma)\cdot T_q(1 + r)^\gamma \cdot P(S = Y) \quad (20)$$

where $S$ denotes severity in a standardized sequence or the sum of deficits in each epoch of a drought spell. Such deficits can be approximated as normally distributed in view of the central limit theorem. So, the pdf of $S$ can be written in the following form

$$P(S \leq Y) \sim \frac{1}{\sqrt{2\pi} \sigma_S} \exp\left(-\frac{(Y - \mu_S)^2}{2\sigma_S^2}\right) \quad (21)$$

In a drought spell covering $k$ consecutive years then $L = k$ and expressions for the mean, $\mu_S$, and standard deviation, $\sigma_S$, of severity can be written as follows.

$$\mu_s \sim K(\mu_s) \quad (22)$$

$$\sigma_s \sim K(\sigma_s) \quad (23)$$

where $\mu_s$ and $\sigma_s$ are the mean and standard deviation of individual deficits, and $K$ is as defined earlier.

In common with the expression for $E(L_T)$ in Equation(15), an expression for $E(S_T)$ can be written as

$$E(S_T) \sim \int_0^{\gamma} S_T \cdot f(S_T) \cdot dS_T \quad (24)$$

While the pdf of $S_T$ is not known, Equation (24) can still be solved numerically. Firstly, Equation (21) is integrated numerically to determine $P(S \leq Y)$, and then this value is substituted into Equation (20), yielding an estimate of $P(S \leq Y)$. The values of $Y$ have an increment of 0.1 and can range from 0 to 60, where 60 represents infinity in Equation (24). Let these values of $Y$ be designated as $Y_0 = 0, Y_1 = 0.1, Y_2 = 0.2, ..., \infty$, then Equation (24) can be expressed in a numerical integral form as follows:

$$E(S_T) \sim \gamma \cdot \int_0^\gamma S_T \cdot f(S_T) \cdot dS_T \quad (25)$$

where $n_t = 60/0.1$, and $Y_{600} = 60$.

Since values of $E(S_T)$ are standardized and in non-dimensional form, the actual drought severity designated as $D_T$ can be expressed as

$$D = E(S_T)$$

$$D = E(S_T) \cdot C \quad (26)$$

The last portion of this equation can be written as

$$D_T = x_n \cdot C \cdot \frac{q}{q + x} \cdot E(S_T) \cdot x \cdot x_n \cdot F_T \cdot x \quad (27)$$

where $F_T$ can be called the drought frequency factor and be written as

$$F_T = E(S_T) \cdot C \quad (28)$$

It can be seen that Equation (27) is analogous to the flood frequency formula $Q = O \cdot K \cdot Q$ commonly cited in hydrological texts.

3 Application

The Dongzhou reservoir is located on the Chaiven River of the Dawen basin within a downstream reach of the Yellow River. It controls an area of 189 km$^2$. The main water supply is for a 8667 hm$^3$ irrigation scheme, as well as for drinking water. Average annual runoff within the controlled area amounts to 39x10$^6$ m$^3$ with a $C_v = 0.40$. Flows tend to be log-normally distributed with a
negligible dependence (?). The reservoir should meet the demands of a 1 in a 100 year drought. So design involves estimating the volume of water to be stored. Solution of the problem starts by determination \( q \) for \( C_v = 0.40 \) using Table 1. For independent inflows \( r = q \), then values of \( q \) and \( r \) are used in Equations (15) and (16). The value of \( q \) equals 0.58, (? \( 16^2 \times 10^6 \) m\(^3\)) and \( E(L_T) = 7.15 \), so \( F \approx 12.15 \times 0.40 \approx 4.65 \) and

\[
D \approx 0.39 \times 4.65 \times 0.16 \times 1.134 \times 10^6 \text{ m}^3.
\]

If the discharge is normally distributed, then

\[
q \approx 0.5 \times E(L) \approx 5.78 \times 10^6 \text{ m}^3
\]

When discharge is represented by a gamma distribution then results are given by \( q \approx 0.55 \times E(L) \approx 6.74 \), and \( D \approx 1.07 \times 10^6 \text{ m}^3 \).

When \( q \approx 0.5 \), \( r = 0.67 \), \( E(L_T) \approx 8.57 \) and

\[
D_T \approx 1.36 \times 10^6 \text{ m}^3.
\]

While for a gamma distribution of discharge \( q \approx 0.55 \times r \approx 0.71 \),

\[
E(L_T) = 9.92, D_T \approx 1.43 \times 10^6 \text{ m}^3.
\]

These calculations demonstrate the role of skewness and dependence effects on the storage needs during drought periods. Therefore when it is difficult to identify the pdf of a drought variable, the assumption of log-normality allows a conservative design, which is a desirable feature. The assumption of normality leads to a requirement for least storage under identical conditions of \( C_v \) and of the dependence structure of the rainfall or the runoff sequences.

4 Conclusions

(1) A non-normal pdf of a drought variable significantly influences values of expected drought duration \( E(L_T) \) and severity \( E(S_T) \). For identical conditions of \( C_v, C_s, ? \) and \( T \), the extent of increased values of \( E(L_T) \) and enlarged values of \( E(S_T) \) is greatest for a log-normal pdf, followed by the gamma and normal pdfs. Skewness is reflected in increased values of the above parameters in relation to the normal pdf.

(2) To design storage structures for drought periods, one can safely assume \( E(S_T) \approx E(L_T) \), or drought intensity \( \approx 1 \), based on standardized terms, for \( C_v = 0.2 \times 1 \), \( \approx 0 \) returning periods of 25 \( \times 1000 \) years. This approximation leads to a conservative design for water storage facilities during drought periods.

(3) Skewness and dependence in sequences of drought variables enhance extremal drought durations and severities. In particular, the effect of skewness on extreme drought duration is not insignificant, contrary to existing assumptions in the hydrological literature.

(4) A drought frequency formula can be derived to estimate drought severity in relation to return period, which is analogous to the flood frequency formula. The drought frequency factor, \( F_T \), is equal to \([E(S_T)-C_v^{-1}]\) and can easily be computed knowing the pdf, \( C_v \), and \( ? \) of the drought variable and the desired return period \( T \).

References


Patterns of soil water change in farmland with different crop cover on hilly Loess soils in Northwest China

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2 Northwest Sci-Tech University of Agriculture and Forestry, Yangling, Shaanxi, 712100, China.

Abstract
Runoff plots were used to analyze dynamic soil water changes in farmland with different crop cover on the loess hillsides of Changwu County, Shaanxi Province. The aim was to identify the most effective level of crop soil water. During runoff events, the extent of total storage water noticeably increased with increasing depth, but storage in individual 10 cm layers decreased with depth. Below 40 cm depth, changes were very small. For rainfall events with no runoff, no specific wetting trends were evident. The soil water changes in the rainy season were dependent on specific rainfall events and evaporative conditions. Changes in the deeper soil water layers depended on conditions in the upper soil layer, but changes were smaller than those in the upper layer. Infiltration was higher for the smaller slopes, when the crop and soil textural conditions were the same. The soil water conditions before rain had an important role in controlling resultant changes in total soil water storage. The soil water that farm crops consumed was complemented mainly by deep soil water during dry conditions.

Key words Farmland soil moisture hilly loess plateau.

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1 Introduction
Academia Sinica built the runoff plots of Changwu Wangdonggou agricultural ecosystem experimental area in the hilly loess plateau of NW China. They form part of the “Chinese ecosystem research network” (CERN). The boundary between Shaanxi and Gansu provinces is 12 km west of Changwu County, longitude 107°40’30” ~ 42°30” E, at a latitude of 35°12’ ~16’ N. Long term average rainfall for the area is 584.1 mm, and agricultural production mainly depends on natural rainfall. So, understanding the dynamic variation of soil water is important in making use of limited rainfall availability. Success of the rural economy depends on best use of the limited water resources.

2 Materials and methods
2.1 General situation
The 8.3 km² research area is typical of the hilly loess plateau region, which is as semi-arid to warm temperate. Precipitation is concentrated in the period from July to September, representing 55% of annual rainfall. The primary crops are wheat and maize with a cropping index of 116%. The soil has a silt loam texture. It is classified as Malan loess with groundwater at 50~80 m depth. Soils mechanical analysis and soil parameters are given in Tables 1 and 2.

2.2 Runoff plot layout
Eight runoff plots were set out on slopes of 0°, 30’, 1° and 3° having a 5 m width and either 20 or 50 m length. The basic plot conditions are listed in the table 3.

2.3 Runoff measurements
Measurements were made of rainfall amounts and intensities, surface water evaporation, runoff during rainfall events and soil water content measured at different depths. Water contents were determined using time domain reflectometry (tdr). A set of measuring pits were established in every small plot from the crest to of the foot of the slope, according to plot conditions and the numbers of wave leading line, as shown in figure 1. In plots 1 to 3, each measuring pit has sensors buried at 10, 20, 30, 40, 50 and 60cm depths at equivalent locations along each plot. The soil water contents were measured according to a fixed order along the slope, from the crest to the foot of the plot (Figure 1). Times when soil water contents were measured depended on the weather circumstances. With a clear sky, measurements were made once every morning at 8 am. Additional measurements were made before rain events. During rainfall, soil water was measured more frequently for heavy rainstorms. After rain just stopped, measurement intervals were quite short, 30 minutes or an hour. Thereafter intervals were gradually prolonged, returning to the daily routine once changes became slight.
Table 1. Soil mechanical analysis (%)

<table>
<thead>
<tr>
<th>Constitute</th>
<th>Sand grain</th>
<th>Fine sand grain</th>
<th>Powder grain</th>
<th>Inside powder grain</th>
<th>Thin powder grain</th>
<th>Glue grain</th>
<th>The physics glues grain</th>
<th>Soil quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of grain (mm)</td>
<td>1~0.2</td>
<td>0.25~0.05</td>
<td>0.25~0.01</td>
<td>0.01~0.005</td>
<td>0.005~0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.01</td>
<td>Middle gluing soil</td>
</tr>
<tr>
<td>5</td>
<td>2.4</td>
<td>57.0</td>
<td>8.6</td>
<td>17.7</td>
<td>13.2</td>
<td>39.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.08</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Soil water parameters

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Bulk density (g/cm³)</th>
<th>Total pore space (%)</th>
<th>Saturation water content (%)</th>
<th>Field capacity content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0~10</td>
<td>1.23</td>
<td>48.8</td>
<td>45.4</td>
<td>23.9</td>
</tr>
<tr>
<td>10~20</td>
<td>1.19</td>
<td>59.3</td>
<td>45.3</td>
<td>25.9</td>
</tr>
<tr>
<td>20~40</td>
<td>1.24</td>
<td>50.0</td>
<td>55.0</td>
<td>25.4</td>
</tr>
<tr>
<td>40~60</td>
<td>1.17</td>
<td>44.1</td>
<td>48.7</td>
<td>26.9</td>
</tr>
<tr>
<td>Average of whole section</td>
<td>1.21</td>
<td>50.6</td>
<td>48.6</td>
<td>25.5</td>
</tr>
</tbody>
</table>

Table 3. Basic runoff and sediment plot conditions

<table>
<thead>
<tr>
<th>The plot number</th>
<th>Slope</th>
<th>Area</th>
<th>Crop or field</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>30°</td>
<td>5m×20m</td>
<td>Corn field</td>
</tr>
<tr>
<td>2</td>
<td>1°</td>
<td>5m×20m</td>
<td>Bare field</td>
</tr>
<tr>
<td>3</td>
<td>3°</td>
<td>5m×20m</td>
<td>Bare field</td>
</tr>
<tr>
<td>4</td>
<td>30°</td>
<td>5m×20m</td>
<td>Bare field</td>
</tr>
<tr>
<td>5</td>
<td>0°</td>
<td>5m×20m</td>
<td>Stubble field</td>
</tr>
<tr>
<td>6</td>
<td>30°</td>
<td>5m×50m</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>30°</td>
<td>5m×50m</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>30°</td>
<td>5m×50m</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: The "-" means that did not measure.

Figure 1. Arrangement of wave leading line inside a plot
(a. Arrangement of measuring pit in the plot b. Shows the multiplexer cable to different depth of a measuring pit)

Table 3. Rainfall data during runoff

<table>
<thead>
<tr>
<th>Code</th>
<th>Rainfall date (year.,month.day)</th>
<th>Rainfall volume (mm)</th>
<th>Rainfall duration (h)</th>
<th>Highest rainfall intensity mm/h</th>
<th>Number of rainfall events</th>
<th>Rainfall duration per event (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1996.7.27</td>
<td>13.7</td>
<td>3.92</td>
<td>22.2</td>
<td>4</td>
<td>50,10,35,140</td>
</tr>
<tr>
<td>2</td>
<td>1996.7.28</td>
<td>32.3</td>
<td>4.75</td>
<td>58.8</td>
<td>2</td>
<td>260.25</td>
</tr>
<tr>
<td>3</td>
<td>1996.7.31</td>
<td>18.1</td>
<td>1.50</td>
<td>24.0</td>
<td>2</td>
<td>20.70</td>
</tr>
<tr>
<td>4</td>
<td>1996.8.23</td>
<td>23.7</td>
<td>2.83</td>
<td>50.4</td>
<td>1</td>
<td>170</td>
</tr>
<tr>
<td>5</td>
<td>1996.8.26</td>
<td>23.1</td>
<td>15.58</td>
<td>2.4</td>
<td>3</td>
<td>510,120,305</td>
</tr>
<tr>
<td>6</td>
<td>1997.7.05</td>
<td>10.6</td>
<td>3.33</td>
<td>6.0</td>
<td>2</td>
<td>20.180</td>
</tr>
<tr>
<td>7</td>
<td>1997.7.28</td>
<td>19.4</td>
<td>4.83</td>
<td>22.8</td>
<td>3</td>
<td>240,30,20</td>
</tr>
<tr>
<td>8</td>
<td>1997.7.31</td>
<td>8.0</td>
<td>0.83</td>
<td>15.6</td>
<td>2</td>
<td>5.45</td>
</tr>
<tr>
<td>9</td>
<td>1997.8.06</td>
<td>60.6</td>
<td>5.50</td>
<td>18.0</td>
<td>3</td>
<td>110,70,150</td>
</tr>
<tr>
<td>10</td>
<td>1997.8.15</td>
<td>12.5</td>
<td>7.83</td>
<td>4.2</td>
<td>1</td>
<td>440</td>
</tr>
</tbody>
</table>
3 Results
3.1 Field soil water changes during rainfall runoff
The study periods were from July to September, 1996, and May to September, 1997. During 1996, plot 1 contained maize, while plots 2, 3 and 4 were all bare before August 1 then they were planted with maize. The evaporation data during drought conditions extended from May 13th - June 20th in 1997, when plot 1 was in wheat, plots 2 and 3 were in maize and plot 4 was a bare field. Plot surfaces were level rather than ridged. The study period contained 10 days of runoff data, with all rainfall events being listed in Table 3.

Soil water contents before rainfall and soil water distributions along the slope after rainfall are shown in Figure 2.

Figure 2 shows patterns of total water storage change under runoff producing rainfall for three plots. Changes with depth are noticeable at each measuring pit, but the change of total water storage for 10~30 cm is the largest. Changes of total water storage below 40 cm depth are very small. Changes of total water storage with increasing depth (10~20, 20~30, 30~40 and 40~50cm) decrease gradually. For the same depth, change of total water storage water along the slope has no obvious pattern. Analyzing the change of total water storage for 10~50 cm of the whole slope, then plot1 >plot2 >plot3. This shows that cropped soil permits more infiltration of rainwater. Also, for the same crop, the smaller the slope the greater is the infiltration.

### Table 4. Rainfall data for events without runoff

<table>
<thead>
<tr>
<th>Code</th>
<th>Rainfall date (year.month.day)</th>
<th>Rainfall volume (mm)</th>
<th>Rainfall duration (h)</th>
<th>Highest rainfall intensity (mm/h)</th>
<th>Number of rainfall events</th>
<th>Rainfall duration per event (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1996.7.21</td>
<td>2.6</td>
<td>0.5</td>
<td>10.2</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>1996.8.01</td>
<td>9.8</td>
<td>3.67</td>
<td>9.0</td>
<td>2</td>
<td>70 150</td>
</tr>
<tr>
<td>3</td>
<td>1996.8.10</td>
<td>10.4</td>
<td>8.5</td>
<td>10.2</td>
<td>4</td>
<td>85 270 15 140</td>
</tr>
<tr>
<td>4</td>
<td>1996.9.02</td>
<td>3.6</td>
<td>4.67</td>
<td>1.2</td>
<td>1</td>
<td>280</td>
</tr>
<tr>
<td>5</td>
<td>1997.7.01</td>
<td>6.5</td>
<td>4.33</td>
<td>6.0</td>
<td>3</td>
<td>80 130 50</td>
</tr>
<tr>
<td>6</td>
<td>1997.9.23</td>
<td>6.6</td>
<td>10.0</td>
<td>1.8</td>
<td>1</td>
<td>600</td>
</tr>
</tbody>
</table>

3.2 Average soil water contents along the slope, before and after rainfall with no runoff
Rainfall data for events without runoff are shown in Table 4. Figure 3 shows the changes of total water storage at each small plot for rainfall when no runoff occurred. The change of total storage water at each depth along the slope has no obvious pattern under conditions with rainfall producing no runoff. Results reflect the spatial variation of soil water and the non-uniformity of unsaturated flow in farmland conditions. Changes of stored water at different depths along the slope can be large or small, when the amount of rainfall is small.
3.3 Characteristics of farmland soil water changes in the rainy season

The variety of rainfall events in the rainy season is shown in Figure 4 for 1996. Rainfall is concentrated primarily from July to September. The rainfall data are examined for July 21 to August 4 in 1996. In 1996, maize was just beyond the seedling stage in plots 2 and 3 on August 1, so they can be considered as bare plots then. Figure 5 shows the patterns of soil water change at each depth of the whole slope for plots 1~3. Rapid wetting to 50 cm depth is evident on the cropped 3° slope. The 1° degree, bare slope suggests a slower rate of wetting to depth, despite the flatter slope. At 50 cm depth, wetting is restricted on the bare, 3° slope. Otherwise the wetting pattern at different depths is somewhat similar. Evaporation from surface layers limits some water movement to depth and causes greater fluctuation of water storage in the surface layers. The extent of fluctuations decreases with depth. When there is heavy rainfall, the soil water increases, but declines again very quickly, suggesting some macropore flow.

3.4 Soil water changes during drought conditions

Table 5 shows daily evaporation data for May, 1997. In Figure 6, soil water changes are shown for the whole slope on 3° maize fields, every 3 days from May 13th -31st.

Table 5. Daily evaporation of May in 1997 (mm)

<table>
<thead>
<tr>
<th>Date</th>
<th>evaporation (mm)</th>
<th>Date</th>
<th>evaporation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>4.8</td>
<td>23</td>
<td>8.5</td>
</tr>
<tr>
<td>14</td>
<td>6.9</td>
<td>24</td>
<td>6.5</td>
</tr>
<tr>
<td>15</td>
<td>9.4</td>
<td>25</td>
<td>9.3</td>
</tr>
<tr>
<td>16</td>
<td>8.9</td>
<td>26</td>
<td>7.2</td>
</tr>
<tr>
<td>17</td>
<td>7.7</td>
<td>27</td>
<td>9.4</td>
</tr>
<tr>
<td>18</td>
<td>10.6</td>
<td>28</td>
<td>10.4</td>
</tr>
<tr>
<td>19</td>
<td>9.2</td>
<td>29</td>
<td>11.1</td>
</tr>
<tr>
<td>20</td>
<td>5.7</td>
<td>30</td>
<td>9.8</td>
</tr>
<tr>
<td>21</td>
<td>6.0</td>
<td>31</td>
<td>11.3</td>
</tr>
<tr>
<td>22</td>
<td>7.2</td>
<td>Total</td>
<td>159.9</td>
</tr>
</tbody>
</table>
Figure 6 shows that soil water contents gradually decrease at each depth, but changes become smaller. So slope position has no great influence on soil water changes in shallow layers. For layers deeper than 40 cm, the up-slope soil water content changes are large, while in the central and lower parts of the slope then changes are smaller and the differences are very small. This may be linked with transient perched water tables in the sub-soil.

Under long drought conditions, part of the surface layer losses are made good by vapour transfer from deeper layers, reducing the range of shallow soil water changes. From the farmland humidity[] the deeper soil is such as underground reservoir which can accept and save the rain water, so as to guarantee the farm crop absorb and exploitation over a long period of time the dry quarter. The average soil water contents of the 10~60 cm depth were 19%, 17.3%, for the whole slope on May 13 and June 1, respectively, so stored water reduces 8.3 mm. During this period, the evaporation is 159.9 mm. This implies that the surface cover is effective in minimising evaporation.

4 Conclusions
Recently developed techniques have been used to examine patterns of soil water change in a hilly loess area. Under rainfall producing runoff, changes of total water storage water at each measuring pit were noticeable for the 10~30 cm depth. Changes of total water storage decreased with depth. For rainfall producing no runoff, changes of total water storage at each depth along the slope have no obvious pattern.

The influence of cropping on rainfall infiltration was much more significant than slope, for the conditions examined in this experiment. Patterns of surface soil water changes were very dependent on current rainfall and evaporation. Upward vertical flow was not very significant. Fluctuations in water content of deeper soil layers depended on wetting of the shallow soil layer. Larger rainfall events stimulated deeper water penetration. Since the unsaturated loess layer is very deep so it has a large capacity for accommodating changes of water storage. Stored water must be accessed by deep rooting crops.

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Water conditions of plants growing in hilly and gully regions of Loess Plateau

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Abstract
Difference of soil moisture over time and space, together with degrees of water shortage of various plants, were analyzed by measuring soil moisture for 0~180 cm depths on shaded, sunny or semi-shaded hillsides and flat land in the FeiMaHe valley. Result indicated that distribution of soil moisture varied from terrace width to terrace width. Soil moisture of narrow terraces was evenly distribution, but in wide terrace it decreased from inside to outside. It was different from slope direction and slope seat. The soil moisture of shaded hillside was more 111.9 mm than sunny hillside on the average value of year. The soil moisture along slope length was well distribution after constructing narrow terrace. The annual variation of soil moisture could be divided into three stages. These were a very slow variation stage from the beginning of December to the following June, very fast variation stage from the beginning of July to end of August and a slow variation stage from September to the end of October. Changes on shaded hillsides were slower than sunny hillsides. On the other hand, difference of degrees of plant water supply was very large in various standing conditions. Basically, secondary forestry on the middle and lower parts of shaded hillsides did not lack water but that on upper parts did. Maize and fruit tree plots were dry from May and adequacy of supply was 74.4% and 83%, respectively, from April to October.

Key words: Spatial and temporal soil moisture variability; extent of soil moisture sufficiency.

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1 Introduction
1.1 Plateau conditions
Rehabilitation and restoration of the eco-environment of the Loess Plateau has become one of China’s strategic tasks in the new century. But water is a key factor, restricting vegetation rehabilitation and restoration. So now more than any other time, it is urgent to carry on basic research into ‘the relationships between vegetation and water’. In the early 1980s, Yang Wenzhi and Han Renfeng investigated the soil moisture situation of artificial woodland and grassland on the Loess Plateau. Meanwhile, analyses were made of soil physical characteristics and the related water balance. In the late 1990s, Hou Qinchun and Han Rulian made a comprehensive investigation into soil moisture and tree growth, from a forestry angle. This study was based on systematic measurement of watershed soil moisture. The first step was to determine the distribution features and effects of deficiencies of soil moisture on different vegetation stands. So plant growth and existence criteria might be established for this region. This work should lay a foundation for further research on ecological water requirements and rational distribution of vegetation.

1.2 Current watershed land use and vegetation distribution
The research area is Baota district of Yan’an city, lying on the central Loess Plateau in northern Shaanxi. It is a typical hilly and gullied region. The extent of land stratification is very serious, and river valleys amounting to more than 50% of the total area. Total area of Baota district is 354,068 ha, being 26.6% farmland, 4.4% garden plots, 44.3% woodland and 20.5% grassland for grazing. Inside the district, the main crops are corn, fruit trees, fodder grass, and natural secondary forests. The character of present land use here is a majority of farmland on terraced or flat land, with some scattered cultivated hillside land. Orchards are mainly distributed on the tops and slopes of ridges, most of the natural forest stands are on south facing hillside slopes. Fodder grass can be found here and there, but it mainly grows on the south of the slope.

2 Materials and methods
2.1 Experimental arrangements
Based on conditions of vegetation stands and features of land use in the restricted watershed, 17 water observation plots were arranged in April 2001. Locations included south-facing hillsides (apple orchards), north facing hillsides (natural
secondary forests) and west or east facing hillsides (apple orchards). The top middle and bottom sections of slopes on natural grassland were monitored. Inside, middle and outside of cultivated corn terraces of 20m width were included as well as the inside and outside of narrow terraces on south facing hillsides (orchards).

Gravimetric sampling was combined with neutron meter soil water measuring instrumentation (CNC503B-DR). Measurements were taken at 20 cm increments to a depth of 1.8m. Soil moisture was monitored on the first and the 15th day of each month with additional measurements before and after rainfall. Three repeat measurements were taken for each layer. Precipitation was determined by combining normal rain gauges and automatic rain gauges.

2.2 Data analysis
The profile soil water reserve was determined by summing measurements for different layer as follows:

\[ W_i = \omega_i \cdot r_i \cdot h_i; W = \sum W_i \]

where \( W \) — total soil water reserves (mm); \( \omega_i \) — gravimetric soil water content (%); \( r_i \) — dry bulk density (1.35g/cm³); \( h_i \) — depth of each layer (20cm).

3 Results
3.1 Spatial variability of soil moisture
3.1.1 Moisture variation in different widths of terraced fields
There are two typical terraces in the watershed. There is a narrow terrace of 2m width, usually carrying fruit trees. The other is a wide terraced field of 20m width, where corn is the main cultivated crop. The variation of soil water reserves can be seen from Figures 1 and 2, for a growing cycle from the beginning of November 2001 to the end of October 2002. Figure 1 shows that soil water reserves of the wide terrace decrease from inside to outside, at an average rate is 4mm/m. The deviation represents about 25% of soil water reserves. Furthermore, the deviation increases when soil moisture reserves exceed 60% of field capacity. Figure 2 indicates that variation of soil moisture reserves is not significant between inside and outside of narrow terraces. The inside is 15.8 mm higher than the outside on average, representing only a 5% difference. In comparing the wide and narrow terraces, we can obviously see that total water reserves of a narrow terrace are 306.7mm, just 90% of that of a wide terrace. The narrow terrace is as same as the outer fridge of the wide terrace, both of them belonging to well-drained soil water regime.

3.1.2 Variation of soil moisture along the slope
The majority of vegetation is secondary forest on the shaded hillsides; fruit trees are cultivated on the semi-shaded slopes and also in the narrow terraces. Annual variation of soil moisture in the secondary forest and the upper, middle and bottom of the orchard can seen in Figures 3 and 4. Figure 3 indicates that soil moisture reserves of secondary forests vary sharply down slope, with the annual average rate of change being 57%. Soil moisture increases in moving from top to bottom down the hillside, with an annual average rate of 6.06 mm/m. In contrast, from Figure 4, we can see that variation of soil moisture reserves down slope was very small on south facing slopes. Perhaps partly as a consequence of the level steps being built for the orchards, annual average rate of change becomes only 8.8%.
3.1.3 Variation of soil moisture on different hillside directions

Variation of soil moisture reserves in the north and south facing hillsides is also indicated by Figures 3 and 4. In general, moisture in north-facing slopes is far higher than that in south-facing slopes. Over the year, the difference can become as large as 111.9mm. For the same elevation, in comparing north and south facing slopes, the latter soil water profiles were 235.6, 134.6 and 34.5mm larger in moving from bottom to top, respectively.

3.2 Soil moisture variability over time

Change of soil moisture on north and south facing slopes differed from the beginning of November 2001 to the end of October 2002. Figure 3 indicates that change of soil moisture on the north-facing hill slope was slight from the beginning of November to the end of June. Average rate of change was 0.2 mm/d, changing most quickly from the beginning July to the end of August when the rate was 2.25 mm/d. It changed slowly from September to October and the average speed of change was 1.38 mm/d.

Figure 4 indicates that soil moisture of the south-facing hill slope changed slowly from the end of November to June of the next year with an average rate of change of 0.54 mm/d. From the beginning of July to the end of August, there was a sharp change to a rate of 3.04 mm/d. Then change was slow, at an average rate of 1.45 mm/d from September to October.

3.3 Analysis of adequacy of soil crop water

3.3.1 Adequacy of soil moisture for secondary forestry

A standard of 60% of field capacity is chosen, equivalent to 324 mm of stored soil water. If the soil water content of soil is greater than this value, then the crop can absorb adequate soil water to yield satisfactorily. If it is lower than this value, then plants will lack water.

Figure 3 shows stored soil water in the upper, middle, and bottom slopes of the secondary forestry. From November 2001 to March 2002, the store of secondary forestry soil water was higher than 60% field capacity. So the soil water supply is fully adequate. It is also fully adequate at the bottom of the slope for the whole year. The mid-slope position lacked 12.2 mm of water, being 96% adequate. Upper slope locations lacked water from April to October, with 71% adequacy of water supply.

3.3.2 Adequacy of soil water for maize

Figure 1 shows that the changes and extent of adequate soil water for maize between April and October. From November 2001 to April 2002, soil water was 100% adequate but water became seriously lacking between May and October. From April to October, overall adequacy of soil moisture for maize was 81.8, 78.8 and 62.7%, respectively, for the inner, middle and outer sections of terrace.

3.3.3 Adequacy of soil water for the orchards

Figure 4 shows 100% adequacy for apples from November 2001 to April 2002 with serious
shortage between May and October. At that time, the soil water reserves are 83% adequate.

4 Conclusions

(1) Different widths of terrace had different soil water distributions. Soil moisture of the narrow terrace was even in the 0-180 cm soil layer. Soil moisture of the wide terrace decreased from inside to outside.

(2) Soil moisture changed sharply depending on slope direction and position. The annual average of soil moisture in shaded slopes was 111.9 mm higher than that of sunny slopes. By building horizontal steps on the slope, the wide variation of soil moisture along the slope, amounting to 57%, was not experienced.

(3) For crops in different conditions, there are obvious variations in adequacy of soil moisture. For secondary forestry on a shaded slope, water in the mid- and bottom slopes is not scarce and the secondary forestry grows luxuriantly. The upper slopes seriously lack water, so tree density is small but grass grows well. The maize lacks water from April to October. Annual average adequacy of soil water for maize was 81.8, 78.8 and 62.7%, respectively, for the inner, middle and outer sections of terrace. Orchard soil moisture reserves appeared to wane seriously in May but the situation was not so severe as for maize. Annual average adequacy of orchard soil moisture is 83% from April to October.

(4) Soil moisture changed with time. On the whole, soil moisture changes could be divided into three stages. From the beginning of November to June of the next year, soil moisture varied very little. From the beginning of July to the end of August it changed rapidly. From September to October it changed slowly. The soil moisture of shaded slopes changed slower than sunny slopes from the beginning of November to June. Average drying rate of the shaded slope was 0.2 mm/d and 0.54 mm/d for the sunny slope. From the beginning of July to the end of August the average drying rates were 2.25 mm/d and 3.04 mm/d for the shaded and sunny slopes, respectively. From September to October, the average drying rates were 1.38 mm/d and 1.45 mm/d for the shaded and sunny slopes, respectively.

Acknowledgements

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Effective use of rainwater with heliogreenhouse in semi-arid regions of Loess Plateau

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Abstract
Supplementary irrigation needs of cucumber and tomato were determined for on-site rainwater harvesting in semi-arid regions of Loess Plateau, where precipitation exceeds 250mm. Runoff efficiency was determined for a heliogreenhouse with 422 m$^2$ of plastic cover, 120 m$^2$ of tile-covered back roofing and 560 m$^2$ of plastic mulch wastes covering the intermediate space. Estimates were 85.4%, 50% and 45.4% respectively, giving 170 m$^3$ of harvested water. The optimal drip irrigation requirements of cucumber and tomato over the autumn and winter period were 90.5 and 60.8 m$^3$, respectively, for a heliogreenhouse with a net usable area of 425 m$^2$.

Keywords: Heliogreenhouse; rainfall harvesting; efficient use.

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1 Introduction
China’s semi-arid region of the Loess Plateau covers a total area of 626,800 km$^2$, including 5 provinces and 2 autonomous regions, and is the main rain-fed farming region in China. Rain-fed cropland occupies about 80% of the total cultivated land in the Loess Plateau (Shan, 1993). Loosely structured soil, highly susceptibility to wind and water erosion, low rainfall and uneven distribution are dominant factors. This is a fragile eco-environment, with limited sustainable development of agriculture and animal husbandry. Based on these conditions rainwater harvesting techniques have been stimulated and the term rainwater harvesting agriculture (RHA) has been put forward by Zhao Song-ling (1996). The RHA system consists of catchments, runoff channels, sediment tanks, storage containers and supplemental irrigation systems. The aim is increasing effective water for crop growth through capturing rainwater. Studies show that rainwater harvesting offers an effective method of improving agricultural conditions of semi-arid regions (Wei and Bai, 1999). The climate and geography of semi-arid regions of Loess Plateau are favorable for development of the method of RHA (Wei and Wang, 1999; Wang et al., 1999; Li, 1998). RHA suits a rural family’s garden using concrete courts, rooftops and roads for rainwater harvesting. It supplies household water needs and permits the surplus water to be used for irrigation of fruit trees, vegetable and small scale crop land (Li et al., 1999; Feng and Qian, 1999; Liu, 2000; Li, 2000). The yields of corn with the optimal ridge/furrow ratios and plastic mulch increased by 90% compared with traditional culture method (Li, et. al., 2000). Value of vegetable output in a heliogreenhouse produced with harvested water was higher than that of field crops or fruits which irrigation using the same volume of harvested water (Cao, 1999). However, few systematic studies have been conducted on rainfall harvesting systems of heliogreenhouses.

China’s greenhouse is different from that of developed countries and represents an innovation for year-round vegetable cultivation in China’s arid and semi-arid regions. The term heliogreenhouse identifies the sole dependence on solar power for heating. This technique has been extensively applied in China’s cold northern areas between latitudes 30-43$^\circ$N. Many vegetables can be successfully cultured not only in spring and summer but also in winter in China’s cold areas without need for artificial heating. In 1999, it was estimated that over 95% of greenhouses in China are of the heliogreenhouse type. Area of heliogreenhouses was said to have reached 350,000 ha (Zhang and Li, 2000). China’s area of such cultivation has become the largest in the world. The average per capita consumption of vegetable supplied by heliogreenhouses is over 20% of total vegetable consumption. However, since most semi-arid regions of the Loess Plateau are suffering from a shortage of water, it hinders development of heliogreenhouses there. Water shortage in winter is still a limited factor in using heliogreenhouses. The probability of further exploiting RHA in the semi-arid Loess Plateau is investigated, including selection of catchments, storage of harvested rainwater and effective use
for different vegetables in heliogreenhouses.

2 Study site
2.1 Location
The study was conducted at Gao Lan Research Station of Ecology and Agriculture, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, during the years of 1998, 1999 and 2002. The study area is located in the west of the Loess Plateau (36°13'1N, 103°47'1E, elevation 1820 m a.s.l). The regional climate is semi-arid, with mean annual precipitation of about 263 mm and nearly 70% falling between May and September. Mean annual temperature is 8.4 °C with a maximum temperature of 20.7 °C (July) and minimum of −9.1 °C (January). Average annual pan evaporation is 1786 mm. Soil is a silt loam, belonging to the Haplic Orthic Aridisols type.

2.2 Catchments
The heliogreenhouse consists of a back wall, sidewall, back roofing, arch truss, plastic mulch, winter protection channel and warming cover material. In general, the span of a heliogreenhouse is 6-8m, the intermediate distance between two heliogreenhouse is usually 9-10 m. Without building other catchments, the heliogreenhouse itself is a good water collector, the plastic mulch, the back roofing and intermediate area all can be used for harvesting rainwater. In addition, the winter protection channel can transport harvested water to storage containers.

2.3 Runoff efficiency and costs of different catchments
Except for the heliogreenhouse plastic mulch, we must adopt suitable materials and treatments to encourage harvesting at lowest cost. Hence, experiments with different soil surfaces and coving materials were conducted in 1998, 1999 and 2002. Table 1 shows that runoff efficiency of plastic, linoleum and pitch catchments is over 60%, and that minimum runoff-producing rainfall of these catchments is 0.21 mm. Runoff efficiency of catchments having concrete, waste plastic mulch coverings, tile-covering, compacted earth and red sand coverings ranges between 32.1-57.5%. The minimum runoff-producing rainfall of these catchments is between 1.5-4.5 mm. Of these, the heliogreenhouse plastic cover, linoleum, waste plastic mulch, tile and concrete covering not only have high runoff efficiency, but also low cost. From those materials, waste plastic mulch was used to cover the intermediate space between heliogreenhouses. In addition to its high runoff efficiency and low cost, the size of it is same as the intermediate space. For the back roofing, durability and leak-proof properties are considered as well runoff efficiency and costs. Tiling is generally a suitable cover and rainwater harvesting material.

2.4 Harvested rainwater volume
A heliogreenhouse is typically 65m in length and 8.5m wide, giving an area of 553m². Areas of plastic mulch, back roof, preparation room and intermediate space are 422, 130, 20 and 560 m², respectively. Minimum rainfall is typically 250 mm, suggesting an annual collection volume of 170 m³ for the whole greenhouse. Based on $0.18 m⁻³, the total storage cost is $31.2.

2.5 Rainwater storage techniques and installation cost
Irrigation is required in winter and spring, so rainwater harvested in summer and autumn must be stored in the containers. Ponds and cisterns are in common use locally. Table 2 gives typical costs for a range of materials. For a concrete pond within the house and concrete cistern outside, the total storage cost of harvested rainwater collected by the harvesting system is $131, based on a unit cost price of $0.77 m⁻³.

<table>
<thead>
<tr>
<th>Type of catchments</th>
<th>Threshold rainfall (mm)</th>
<th>Runoff volume 1998</th>
<th>Runoff volume 1999</th>
<th>Runoff volume 2002</th>
<th>Runoff efficiency %</th>
<th>Cost price (300mm/year)</th>
<th>$. m⁻³ (Total fees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compact mixed earth</td>
<td>9.5</td>
<td>19</td>
<td>34</td>
<td>-</td>
<td>8.6</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td>Clean weeded</td>
<td>8.0</td>
<td>33</td>
<td>40</td>
<td>-</td>
<td>12.3</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>Plastic film mulch</td>
<td>0.13</td>
<td>144</td>
<td>262</td>
<td>-</td>
<td>66.6</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td>Pitch</td>
<td>0.17</td>
<td>167</td>
<td>29</td>
<td>-</td>
<td>61.2</td>
<td>0.82</td>
<td></td>
</tr>
<tr>
<td>Linoleum</td>
<td>0.21</td>
<td>188</td>
<td>279</td>
<td>-</td>
<td>77.7</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td>Natural slope</td>
<td>8.5</td>
<td>28</td>
<td>30</td>
<td>-</td>
<td>9.8</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>1.48</td>
<td>117</td>
<td>237</td>
<td>-</td>
<td>57.5</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td>Red-sand mulch</td>
<td>4.5</td>
<td>-</td>
<td>-</td>
<td>100</td>
<td>37.7</td>
<td>0.24</td>
<td></td>
</tr>
<tr>
<td>Waste plastic cover</td>
<td>3.0</td>
<td>-</td>
<td>-</td>
<td>120</td>
<td>45.4</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td>Tile-covered</td>
<td>3.3</td>
<td>-</td>
<td>-</td>
<td>115</td>
<td>43.5</td>
<td>0.41</td>
<td></td>
</tr>
<tr>
<td>Plastic mulch</td>
<td>0.10</td>
<td>-</td>
<td>-</td>
<td>226</td>
<td>85.4</td>
<td>0.12</td>
<td></td>
</tr>
<tr>
<td>Compact earth</td>
<td>4.1</td>
<td>34</td>
<td>122</td>
<td>-</td>
<td>32.1</td>
<td>0.06</td>
<td></td>
</tr>
</tbody>
</table>

Note: Precipitation for 1998, 1999 and 2002 was 253, 344 and 265 mm, respectively.
The cost price of harvested rainwater = Runoff volume of unit area / building cost / used life (Year)
Table 2. Storage costs of different containers

<table>
<thead>
<tr>
<th>Type</th>
<th>Capacity (m$^3$)</th>
<th>Time used (yr)</th>
<th>Construction cost ($)</th>
<th>Storage cost (Dollar. m$^{-3}$)</th>
<th>Capacity is less than:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thick plastic covering sand mixed Cement wall cistern</td>
<td>30</td>
<td>5</td>
<td>59.0</td>
<td>0.39</td>
<td>30 m$^3$</td>
</tr>
<tr>
<td>Concrete crust covering cistern</td>
<td>30</td>
<td>8</td>
<td>117.1</td>
<td>0.49</td>
<td>30 m$^3$</td>
</tr>
<tr>
<td>Concrete crust covering brick wall pond</td>
<td>30</td>
<td>10</td>
<td>211.4</td>
<td>0.70</td>
<td>30 m$^3$</td>
</tr>
<tr>
<td>Concrete crust covering adamic Earth cistern</td>
<td>50</td>
<td>8</td>
<td>195.2</td>
<td>0.49</td>
<td>50 m$^3$</td>
</tr>
<tr>
<td>Concrete pond</td>
<td>30</td>
<td>15</td>
<td>357.1</td>
<td>0.79</td>
<td>100 m$^3$</td>
</tr>
<tr>
<td>Concrete cistern</td>
<td>100</td>
<td>15</td>
<td>1142.9</td>
<td>0.76</td>
<td>100 m$^3$</td>
</tr>
</tbody>
</table>

Table 3. Optimal irrigation volume, quota, yield and irrigation water efficiency of cucumber, tomato and hot pepper with drip irrigation in heliogreenhouse

<table>
<thead>
<tr>
<th>Variety</th>
<th>Irrigation water use efficiency (kg.ha.mm$^{-1}$)</th>
<th>Yield of unit water (t.m$^{-3}$)</th>
<th>Yield (t.ha$^{-1}$)</th>
<th>Irrigation quota (mm/application)</th>
<th>Irrigation frequency</th>
<th>Optimum irrigation volume (mm.425m$^{2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cucumber</td>
<td>0.068</td>
<td>145.8</td>
<td>18</td>
<td>17</td>
<td>9</td>
<td>213</td>
</tr>
<tr>
<td>Tomato</td>
<td>0.037</td>
<td>53.6</td>
<td>10</td>
<td>11</td>
<td>6</td>
<td>143</td>
</tr>
<tr>
<td>Hot pepper</td>
<td>0.027</td>
<td>20.2</td>
<td>5</td>
<td>12</td>
<td>5</td>
<td>75</td>
</tr>
</tbody>
</table>

3 Effective use of harvested rainwater

Studies have shown that when drip irrigation with film mulch is compared with surface irrigation, the water volume is reduced by 60-70% (Mao and Li, 2000; Xu et. al., 2001; Cheng et.al,1998) and house air humidity inner is reduced by 10-15% (Mao and Li,2000), with disease control benefits. Local experiments with cucumber, tomato and hot pepper suggest that optimal irrigation volumes for the autumn-winter greenhouse season was 90.5 m$^3$, 60.8 m$^3$ and 31.9 m$^3$, respectively. This is based on a cultivated area of 425 m$^2$. Crop yield, response and water use efficiency of these vegetables are shown in Table 3.

4 Conclusion

Rainwater harvesting system of heliogreenhouse is a new exploration of effective use of rainwater, in this system, the installation of heliogreenhouse be utilized further, the cost price of the harvested rainwater was reduced and be used effectively from the changing of time and space distribution of rainfall, with this techniques, rely on the natural rainfall resource, the installation agriculture can be exploited in semiarid rain-fed region of the Loess Plateau and produce high value products in cold seasons.

In semiarid regions which the precipitation exceeds 250mm, the harvested rainwater volume of rainwater harvesting system of heliogreenhouse can not only meet the irrigation demand of cucumber or tomato or hot pepper which culture in heliogreenhouse in autumn and winter, but also can meet the irrigation demand of a crop rotation of cucumber—tomato, cucumber—hot pepper or tomato—hot pepper.

The studies of rainwater harvesting system of heliogreenhouse is preliminary at present, the materials of catchments, store and effective use techniques of harvested rainwater should be research further.

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Rainwater catchments and efficient use of water storage for irrigating greenhouses on hillside fields of a semi-arid area

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Abstract
An experiment was carried out on Xishan watershed in the hilly semi-arid area of west Liaoning. It aimed to study the efficiency of water use from a rainwater catchment with dam-pond and water storage cellars for irrigating greenhouses on hillside fields. The recommended structures for rainwater harvesting include dam-cisterns in gullies, cellars grouped on the hillside and stream flow gathering points. All have optimal designs. Results showed that, on average, the rainwater storage efficiency was 12.9% and sediment yield amounted to 2130 kg·hm⁻². For vegetable growing over 100 days, 100 m³ of storage was sufficient to satisfy an effective sub-surface irrigation area of 500 m² in each greenhouse. The water used was only 50% of that for flood irrigation. The output values of water and land were 96 yuan·m⁻³ and 15 yuan·m⁻² respectively, which were about 10 times higher than those for traditional land use. By using integrated techniques, three goals were realized. These were reducing water and soil losses, getting high efficiency of rainwater use and gaining corresponding benefits.

Key words: Hilly semi-arid area; rainwater storage; greenhouse on hillside field; cellar-greenhouse system

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1 Introduction
The hilly semi-arid area is contiguous with the provinces of Liaoning, Hebei and Inner Mongolia, together with their surrounding regions. It covers about 1.1×10⁶ km² and belongs to an area with a fragile ecological environment and weak economic base. It is rich in solar energy but lacks of water. There are serious limitations on sustainable agricultural development in this area [2000]. Ecological construction to enhance the rate of rainfall use and to control soil erosion is a key measure for promoting regional sustainable agricultural development. Although protected cultivation and terrace farming techniques help to maintain soil moisture and increase output, drought and lack of water can not be solved by these techniques used individually. Sowing can be delayed and the productive potential of land is not fully met. Efficiency of the limited water resources is low due to runoff on hillside fields and high evaporation. Controlling erosion on sloping land through structured land use, along with beneficial rainfall interception, forms the basis of developing efficient agriculture in the area.

2 Experimental area
Experiments were conducted at the Xishan watershed in western Liaoning, which is typical of the hilly semi-arid area. Mean annual precipitation is about 500 mm, mean annual temperature is 8.2 °C, with 2900 annual sunshine hours. Effective accumulated temperatures above 0°C and 10°C are 3839.4 °C and 3431.8 °C respectively, with a frost-free period of 152 days. The soil type is cinnamon with organic matter in the top 20 cm layer being below 1%. The major crops are maize, millet and sorghum but with low yields due to aridity and serious soil erosion.

3 Catchment engineering design of cellar-green house

3.1 Design principles
Rainwater catchment engineering involves use of a cellar-greenhouse system made up of four parts. These are a rainwater-collecting site, sediment intercepting dam-cistern, cellar for storing rainwater and a greenhouse on the hillside fields. Rainwater runoff from sloping fields, gullies or stream flow is collected to efficiently irrigate vegetables in greenhouses on hillside fields. This is the so-called “cellar-greenhouse” system. It combines principles of technical integration of rainwater catchment, accumulative storage and efficient use (Li et al., 1999; Wu et al., 2002; Sasmra, 1997). The unevenly distributed rain, which is easily lost, is converted into a relatively stable and sustainable water supply. It can produce economic, environmental and social benefits with limited water resources.
(1) Ecological system management.
Consideration of soil and water conservation, irrigation and efficient agriculture is treated in a holistic way to optimise the combination of component parts.

Measures suited to local conditions. Local topography and rainfall runoff is used to best advantage in rainwater harvesting.

Emphasis on benefits and efficient water use. The aim is greatest economic, environmental and social benefit.

(4) Simplicity and practicability.
The characteristics are simple construction, low cost and easily mastered. It accords with the need for dispersed management and small hydraulic engineering development. It may be popularised across a wide area as well.

3.2 Classification of rainwater catchment engineering

3.2.1 Engineering of cellars grouped on the hillside (CGH).

The hillside is not only the major site of runoff production, but also the key area of soil erosion. Soil conservation measures allow runoff in a controlled fashion but there is still runoff. At the same time, there are other uncontrolled pieces of sloping land. All of these are potential rainwater catchments. The volume and numbers of cellars can be determined based on area of hillside catchment and estimate of likely total rainwater collection.

3.2.2 Engineering of dam-cellars in gullies (DCG).

Check dams have been adopted for controlling gully erosion, but intercepted runoff is seldom effectively used for agricultural production. By first constructing a dam-pond for collecting runoff and intercepting sediment in narrow parts of a gully, then there is opportunity to build cellars for water storage downstream of a dam-pond (Gao et al., 2002).

3.2.3 Engineering of stream flow gathering points (SGP).

There is usually some subsurface runoff or spring flow which emerges at a gully or base of a slope. Such sources are also linked for use in greenhouses.

3.3 Estimation of rainwater catchment engineering potential

Design of rainwater catchment engineering components is based on the following estimates of potential.

3.3.1 Estimation of catchment potential (CGH)

\[ W = RK \frac{PS}{1000} \]

\( W \) — potential catchment runoff (m³);

\( R \) — runoff coefficient;

\( K \) — modular coefficient;

\( P_0 \) — mean annual precipitation (mm);

\( S \) — rainwater collection area (m²).

3.3.2 Estimate of spillway design (DCG)

The peak flood discharge of dammed gullies is required to design spillways. It is calculated using the following formula.

\[ Q = 0.2787SF/t^n \]

\( Q \) — peak flood discharge (m³ s⁻¹);

\( S \) — catchment area (km²);

\( t \) — catchment time (h);

\( n \) — flood index.

3.3.3 Groundwater supply potential (SGP)

\[ Q = KJW \]

\( Q \) — groundwater flow (m³ s⁻¹);

\( J \) — groundwater hydraulic gradient;

\( K \) — coefficient of permeability;

\( W \) — discharge area (m²).

4 Rainwater catchment and efficient use of cellar-greenhouse

4.1 Effects of rainwater catchment and sediment interception

4.1.1 Rainwater catchment efficiency

Rainwater catchment efficiency means the ratio of the collection capacity in relation to the rainfall amount (Khai and Spank, 1997; Li, 2002). It is related to rainfall characteristics, topography and landforms. Table 1 suggests that rainwater-collecting sites on sloping croplands can only collect runoff from several of the larger rainfall events. On slopes of 6°, the range of rainwater catchment efficiencies is 9.4%—15.1% for collection amounts of 435 m³ hm⁻², but amounts were very small on 4.5° slopes. So use of natural slopes greater than 6° is recommended for collection sites. Areas should be sufficiently large to gain enough runoff for a viable production level. Table 1 shows that, for 2001–2002, rainwater collected in a dam-pond was 2126 m³ from 8 rainfall events exceeding 30 mm, with an annual rainwater catchment efficiency of 14.1%. The largest rainfall event was 52.7 mm, for which 1350 m³ was collected. This amounted to 63% of the total annual storage.

Amounts of water collected from stream flow gathering points were stable. The experiment shows that highest water levels in watersheds of the Xigou and Shajingou were 1.5 m and 1.3 m. This can satisfy the irrigation requirement for a single application on an effective area of 1.0 hm² and 0.8 hm² in greenhouses on hillside fields. Recovery to the peak water levels seemed possible before the next irrigation requirement, their groundwater flows were 18 m³ d⁻¹ and 15 m³ d⁻¹.

4.1.2 Sediment interception

Rainfall runoff is collected through rainwater collecting systems that also accumulate sediment.
The average sediment yield from the sloping croplands is about 1603 kg hm\(^{-2}\), and the sediment yield from the gully is 2658 kg hm\(^{-2}\) (Table 1). So, average sediment yield for the cellar-greenhouse system is 2130 kg hm\(^{-2}\).

### Table 1. Effects of rainwater catchment and sediment interception in the cellar-greenhouse system

<table>
<thead>
<tr>
<th>Collecting site type</th>
<th>Area (hm(^2))</th>
<th>Slope (°)</th>
<th>Total rainfall (mm)</th>
<th>Total runoff (m(^3))</th>
<th>Total sediment (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste sloping land</td>
<td>0.50</td>
<td>4.5</td>
<td>377.3</td>
<td>258.1</td>
<td>832.9</td>
</tr>
<tr>
<td>Sloping cropland 1</td>
<td>0.30</td>
<td>6.0</td>
<td>377.3</td>
<td>106.3</td>
<td>538.2</td>
</tr>
<tr>
<td>Sloping cropland 2</td>
<td>0.52</td>
<td>6.5</td>
<td>377.3</td>
<td>146.0</td>
<td>894.2</td>
</tr>
<tr>
<td>Sloping cropland 3</td>
<td>0.41</td>
<td>6.0</td>
<td>377.3</td>
<td>144.9</td>
<td>717.4</td>
</tr>
<tr>
<td>Sloping cropland 4</td>
<td>0.35</td>
<td>7.0</td>
<td>377.3</td>
<td>199.2</td>
<td>922.5</td>
</tr>
<tr>
<td>Sloping cropland 5</td>
<td>0.42</td>
<td>4.5</td>
<td>377.3</td>
<td>29.8</td>
<td>140.8</td>
</tr>
<tr>
<td>Gully</td>
<td>4.00</td>
<td>3.81</td>
<td>377.3</td>
<td>2126</td>
<td>10631</td>
</tr>
</tbody>
</table>

* Sediment yield=Total sediment/Area.

### 4.2 Rainwater irrigation efficiency in the cellar-greenhouse system

Both sub-surface irrigation and flood irrigation were adopted in the rainwater catchment’s irrigation experiment. Basin dimensions were 7m × 1m, with irrigation supply pipes at 1 m spacing inside greenhouses of 50m×7m or 80m×7m on hillside fields (Table 2). The crops grown were cucumber and tomato. Results indicated that for flood irrigation the irrigation quotas of cucumber and tomato were 459 mm and 327 mm respectively, and that a 200m\(^2\) cellar can satisfy a flood irrigation area of 500m\(^2\) in a greenhouse for a vegetable growing period of 100 days. However, under sub-surface irrigation, the irrigation quotas of cucumber and tomato are 213 mm and 163.5 mm respectively, and a 100 m\(^2\) cellar can satisfy a sub-surface irrigation area of 500m\(^2\) in a greenhouse for a vegetable growing period of 100 days. Compared with flood irrigation, over 50% of the irrigation water is saved by sub-surface irrigation, and water use efficiency is improved by 1.6 kg m\(^{-3}\) on average. In addition, results show that 75% of the supply distributes itself in the 10–50 cm soil layer, with about 10% in the top 0–10 cm layer and 15% at 50–80 cm depth (Liu et., 2002). So leakage from the deep layer is likely to be minimal for sub-surface irrigation, and evaporation is decreased. Moreover, the irrigation takes advantage of natural-flow channels, which are based on natural landfall. Both machines and energy are unnecessary. The economic benefits, wide application and high water use efficiency are obvious.

### Table 2. Water use efficiencies of different irrigation types in the cellar-greenhouse system

<table>
<thead>
<tr>
<th>Vegetable</th>
<th>Area (m(^2))</th>
<th>Irrigation type</th>
<th>Irrigation interval (d)</th>
<th>Irrigation frequency (times)</th>
<th>Individual irrigation amount (m(^3))</th>
<th>Irrigation quota (mm)</th>
<th>Water use efficiency (kg/m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cucumber1</td>
<td>350</td>
<td>Flood irrigation</td>
<td>8</td>
<td>25</td>
<td>6.12</td>
<td>459</td>
<td>1.32</td>
</tr>
<tr>
<td>Cucumber2</td>
<td>350</td>
<td>Sub-surface irrigation</td>
<td>3</td>
<td>70</td>
<td>1.07</td>
<td>213</td>
<td>3.20</td>
</tr>
<tr>
<td>Cucumber3</td>
<td>560</td>
<td>Flood irrigation</td>
<td>8</td>
<td>25</td>
<td>9.79</td>
<td>459</td>
<td>1.56</td>
</tr>
<tr>
<td>Tomato1</td>
<td>350</td>
<td>Flood irrigation</td>
<td>11</td>
<td>18</td>
<td>6.00</td>
<td>327</td>
<td>2.06</td>
</tr>
<tr>
<td>Tomato2</td>
<td>350</td>
<td>Sub-surface irrigation</td>
<td>4</td>
<td>50</td>
<td>1.14</td>
<td>164</td>
<td>3.50</td>
</tr>
</tbody>
</table>

### 4.3 Influence on soil properties and ecological environment in the cellar-greenhouse system

Table 3 compares differences of soil properties under either sub-surface irrigation or flood irrigation. Compared with flood irrigation, soil bulk density is significantly less by 0.10 g.cm\(^{-3}\) (F \(\neq 20.07>F_{0.01}=7.09\) and soil porosity is greater by 4.9% [\(F=13.20>F_{0.01}=7.09\)] under sub-surface irrigation. Results also indicate that there is a 8.3 cm depth of compacted soil along with ground crack widths of 5 mm after 4 days caused by flood irrigation.

Sub-surface irrigation is superior to flood irrigation with respect to keeping the soil surface drier, reducing evaporation a little, decreasing relative humidity and the related occurrence of diseases.

The relative humidity is about 80% throughout the whole growth period of cucumbers, and average daily evaporation is 1.01mm for sub-surface irrigation in the cellar-greenhouse (Table 4). However, relative humidity reached more than 90% after 3–4 days of flood irrigation, and the average daily evaporation was 2.5mm. Sub-surface irrigation results in soil temperatures being higher 1.4°C and prompts a 75% reduction in crop disease compared with flood irrigation.
means lower cost and an improved quality of vegetables entering the market early.

Table 3. Effect of irrigation type on soil properties within the cellar-greenhouse system

<table>
<thead>
<tr>
<th>Vegetable</th>
<th>Irrigation type</th>
<th>Soil bulk density (g cm(^{-3}))</th>
<th>Soil porosity (%)</th>
<th>Ground crack width (mm)</th>
<th>Thickness of hardened soil (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cucumber</td>
<td>Flood irrigation</td>
<td>1.22</td>
<td>51.3</td>
<td>5.0</td>
<td>8.3</td>
</tr>
<tr>
<td>Cucumber</td>
<td>Sub-surface irrigation</td>
<td>1.12</td>
<td>56.2</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Table 4. Effect of irrigation type on ecological environment within the cellar-greenhouse system

<table>
<thead>
<tr>
<th>Vegetable</th>
<th>Irrigation type</th>
<th>Air relative humidity (%)</th>
<th>Evaporation rate (mm d(^{-1}))</th>
<th>Soil temperature (°C)</th>
<th>Disease* generation frequency (times)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cucumber</td>
<td>Flood irrigation</td>
<td>90</td>
<td>2.50</td>
<td>20.8</td>
<td>4</td>
</tr>
<tr>
<td>Cucumber</td>
<td>Sub-surface irrigation</td>
<td>80</td>
<td>1.01</td>
<td>22.2</td>
<td>1</td>
</tr>
</tbody>
</table>

\*Rotten and Aerugo.

4.4 Economic Benefits of the Cellar Greenhouse System

Use of sloping fields is changed by the cellar-greenhouse system and land productivity is increased to a great extent. Greenhouses of 350 m\(^2\) on hillside fields produced 2145 kg of cucumbers and 2240 kg tomatoes, valued at RMB 6435 yuan and 5824 yuan, which is about 10 times higher than that of the traditional land use system (Table 5).

However, the economic benefits of different irrigation types also differ. Sub-surface irrigation increased vegetable yield by 12.4%, while water productivity was 142.2% greater compared with flood irrigation. So water-saving practices such as sub-surface irrigation, should be applied in rainwater catchment irrigating greenhouse on hillside fields to produce larger economic benefits from the limited water resources.

Table 5. Economic benefits of rainwater catchment water in the cellar-greenhouse system

<table>
<thead>
<tr>
<th>Vegetable</th>
<th>Area (m(^2))</th>
<th>Irrigation type</th>
<th>Irrigation amount (m(^3))</th>
<th>Yield (kg)</th>
<th>Economic benefit (yuan)</th>
<th>Output value of water (yuan·m(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cucumber</td>
<td>350</td>
<td>Flood irrigation</td>
<td>153</td>
<td>2020</td>
<td>6060</td>
<td>39.61</td>
</tr>
<tr>
<td>Cucumber</td>
<td>350</td>
<td>Sub-surface irrigation</td>
<td>71</td>
<td>2270</td>
<td>6810</td>
<td>95.92</td>
</tr>
<tr>
<td>Tomato</td>
<td>350</td>
<td>Flood irrigation</td>
<td>109</td>
<td>2240</td>
<td>5824</td>
<td>53.43</td>
</tr>
</tbody>
</table>

5 Conclusions

The hilly semi-arid region of north China has large areas of mountain land, with small amounts of concentrated rainfall and soil and water loss is very serious there. Hence its natural conditions and landform characteristics are advantageous for rainwater collection and storage. The goals of reducing water and soil loss, achieving high water use efficiency and economic benefit can be met with a cellar-greenhouse system constructed on hillside fields and using sub-surface irrigation. So rainwater-harvesting agriculture has a broad appeal in the hilly semi-arid areas.

Since amount of collected rainwater is limited, the cellar-greenhouse system should be integrated with water-saving irrigation practices. Results have shown that a cellar of 100 m\(^3\) capacity can satisfy a sub-surface irrigation area of 500 m\(^2\) in a greenhouse for a vegetable growing period of 100 days. Compared with flood irrigation, the water saving of sub-surface irrigation is 50% and it can improve water use efficiency by 1.60 kg·m\(^{-3}\) on average.

Economic benefits of the cellar-greenhouse system are significant, with water productivity values of RMB 39.6–95.9 yuan·m\(^{-3}\). With a value of RMB 15 yuan·m\(^2\), the productivity of land is significantly enhanced.

References


conference on rainwater catchment systems, Tehran, Iran, pp16~25.
Increasing effective rainfall in representative fields of Beijing Plain

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Abstract

Field data for the plain south-east of Beijing was examined to determine the extent to which a fall in local groundwater tables offered opportunity for greater rainfall interception. Potential storage was usually considered for a 3 m soil depth. Before the rainy season in the years 1991-1995, there was a potential storage capacity of 137 mm for a 2 m depth or 189 mm for a 3 m depth. Results have shown that a drier soil profile has the characteristics of a reservoir, with 85% of normal annual precipitation currently being stored in a 3m depth. So if appropriate measures are taken before an extraordinary rainstorm, then there will be less surface runoff and most of the precipitation will be stored in soils.

Key words: Well irrigation fields; soil reservoir; precipitation and runoff; saturation deficit.

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1 Introduction

1.1 The local environment

The experimental area lies in the Tian Tang river basin of Da Xing county, Beijing. It has a total area is 422.5 km\textsuperscript{2}, and forms part of the Yong Ding river alluvial flood plain. The annual average rainfall is 556.3 mm, with a rainy season from June to September, when about 80% of the annual precipitation might be expected. The precipitation between years varies greatly. The rainfall may be 1000 mm in a wet year but less than 300 mm in a dry year.

During the 1950’s, precipitation was more abundant than usual, and the area was affected by the high level of the Yong Ding river, an imperfect drainage system and limited use of ground water. All this led to a high ground water table, and in some areas the groundwater became springs. So shallow layer evaporation increased rapidly, while flood and water-logging disasters happened frequently.

During 1960-1970, in the experimental area we put emphasis on land-leveling, enlarging the area of gravity irrigation field, modifying the drainage systems and we developed well-irrigation. The ground water table was controlled to some degree. But the water diverted from rivers was excessive, which limited the use of ground water, so the ground water table remained high for a long time. Opportunity for water storage in the soil profile was poor. There was still large area of saline land and 9 waterlogging disasters occurred over a period of 20 years, greatly restraining the development of agriculture.

Since the 1980s, the area has become a complete well-irrigation field. Ground water was intensively explored, leading to a well and ditch network system with irrigation wells to promote drainage and field ditches to provide storage. General surveys show that by 1994, the ground water table has fallen to 7-13m depth. With the descent of the ground water table, the thickness of an aeration zone increased and the potential storage capacity of soil and underground reservoir were greatly strengthened. Evaporation loss was also minimized. Great progress was made possible in harnessing saline-alkali farmlands.

1.2 Finite depth of soil reservoir

Generally speaking, a soil reservoir means the whole-unsaturated layer. Storage capacity depends on soil type and thickness of the unsaturated layer. The water held is mainly capillary water. The “reservoir” storage takes part in a number of physical processes, namely evaporation, infiltration, plants uptake and evapotranspiration. In considering soil water use by plants, it maybe sensible to take maximum rooting depth as the depth of this soil reservoir. Firstly this water layer can be directly used and secondly the water in this layer takes part in a water circulation, while the water stored in deeper layers only changes slightly. Considering most plants, the limiting rooting depth is within 2-3m. In the experimental area, analysis of soil water content data proves that changes deeper than 3m are very slight and can be ignored. So, we take the 0-3m depth as soil reservoir depth, and study its water storage capacity.
Soil storage capacity is the water volume that soil can hold, and its value mainly depends on soil type and structure, effects of farming operations and depth to the ground water table. Rooting depth can be chosen as the depth of such a soil reservoir. Overall storage levels might be identified by three indices, saturation, field capacity and wilting point. The saturation moisture content is the soil’s maximum holding capacity. For crops, field capacity is the normal storage capacity, while wilting moisture content is considered as “dead storage”. The difference between them is the available moisture content, comparable to efficient storage capacity of a surface reservoir.

### Table 1. Comparison between soil and surface reservoirs

<table>
<thead>
<tr>
<th>Technical index</th>
<th>Surface reservoir</th>
<th>Soil reservoir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dead storage ((V_d))</td>
<td>Storage below dead water level ((H_d))</td>
<td>Wilting soil moisture content</td>
</tr>
<tr>
<td>Regulation storage ((V_r))</td>
<td>Volume between dead water level ((H_d)) and normal storage water level ((H_s))</td>
<td>Difference between field capacity and wilting point</td>
</tr>
<tr>
<td>Flood control storage ((V_f))</td>
<td>Volume between normal storage water table and flood-control high water level</td>
<td>Difference between saturation and field capacity (air capacity)</td>
</tr>
<tr>
<td>Maximum storage</td>
<td>Sum of (V_d), (V_r), (V_f)</td>
<td>Saturation</td>
</tr>
<tr>
<td>Maximum storage under normal operation</td>
<td>(V_r + V_f)</td>
<td>Difference between saturation and wilting point</td>
</tr>
<tr>
<td>Regulation volume</td>
<td>Sum of added water volume after a flood</td>
<td>Sum of increased value after every rainfall or irrigation</td>
</tr>
</tbody>
</table>

#### Figure 1. Contrast between surface and soil reservoirs

1.3 **Soil water storage before and after spring irrigation**

Within a soil depth \(H\) m, with gravimetric water contents of \(\theta\) (h) at each depth h, then summing amounts of water stored in each layer can assess current total storage. Local data shows that typical soil dry bulk densities (\(\gamma\)) are of the order 1.43 g/cm\(^3\). So to express storage amounts (\(W_a\)), in mm water, then \(W_a = 10 \times \theta (t) \times \gamma\) should be used, where “10” is a conversion coefficient; \(\theta (t)\) is gravimetric soil water content at a certain time; \(\gamma\) is the dry soil bulk density, units: g/cm\(^3\). Values of saturation deficit can also be obtained by summing the difference of soil saturation levels less current storage, for each of the soil layers. Two times were chosen as being representative of soil storage and saturation deficit conditions. They are the first ten days of March and the first ten days of June. The results are shown in Table 2 and Table 3.

From the tables we can see that during the period of 1992-1995, at the driest time in spring, average soil water storage was 504 mm in a 2 m soil layer and 817 mm in a 3 m soil layer. In 1992 the highest value attained was 571 mm for 2 m and 895 mm for 3 m. While in 1994 the lowest value of 449 mm was recorded for 2 m and 746 mm for 3 m. With abundant rain in 1991 totaling 702 mm, so soil water content was replenished in the spring of 1992 to 20.9%. But
Table 2. Water storage and saturation deficit for 3 m soil depth in the first ten days of March

<table>
<thead>
<tr>
<th>Year</th>
<th>Actual storage in 0-2m layer</th>
<th>Actual storage in layer 0-3m</th>
<th>Saturation deficit v_{ae}</th>
<th>Annual rain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>θ_1 (%)</td>
<td>w_a(mm)</td>
<td>θ_1 (%)</td>
<td>w_a(mm)</td>
</tr>
<tr>
<td>1992</td>
<td>20.0</td>
<td>571</td>
<td>20.9</td>
<td>895</td>
</tr>
<tr>
<td>1993</td>
<td>17.1</td>
<td>490</td>
<td>18.4</td>
<td>790</td>
</tr>
<tr>
<td>1994</td>
<td>15.7</td>
<td>449</td>
<td>17.4</td>
<td>747</td>
</tr>
<tr>
<td>1995</td>
<td>17.6</td>
<td>504</td>
<td>19.6</td>
<td>839</td>
</tr>
<tr>
<td>Average</td>
<td>17.6</td>
<td>504</td>
<td>19.1</td>
<td>817</td>
</tr>
</tbody>
</table>

Table 3. Water storage and saturation deficit for 3 m soil depth in the first ten days of June

<table>
<thead>
<tr>
<th>Year</th>
<th>Actual storage in 0-2m layer</th>
<th>Actual storage in 0-3m layer</th>
<th>Saturation deficit v_{ae}</th>
<th>Annual rain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>θ_1 (%)</td>
<td>w_a(mm)</td>
<td>θ_1 (%)</td>
<td>w_a(mm)</td>
</tr>
<tr>
<td>1992</td>
<td>17.7</td>
<td>506</td>
<td>19.2</td>
<td>823</td>
</tr>
<tr>
<td>1993</td>
<td>22.1</td>
<td>631</td>
<td>22.3</td>
<td>958</td>
</tr>
<tr>
<td>1994</td>
<td>17.4</td>
<td>496</td>
<td>18.4</td>
<td>789</td>
</tr>
<tr>
<td>1995</td>
<td>18.9</td>
<td>517</td>
<td>19.8</td>
<td>850</td>
</tr>
<tr>
<td>Average</td>
<td>18.8</td>
<td>537</td>
<td>19.9</td>
<td>855</td>
</tr>
</tbody>
</table>

Table 4. Rainfall process during July 2~12, 1994, in experimental area

<table>
<thead>
<tr>
<th>Date</th>
<th>2nd-3rd July</th>
<th>5th July</th>
<th>7th July</th>
<th>8th July</th>
<th>11th July</th>
<th>12th July</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain (mm)</td>
<td>46.9</td>
<td>20.7</td>
<td>106.5</td>
<td>10.1</td>
<td>16.6</td>
<td>132.5</td>
<td>333.3</td>
</tr>
</tbody>
</table>

1992 and 1993 were dry years, and the precipitation was 419 and 317 mm, respectively, leading the lowest water content during the period. In 1991, soil water content in the 3 m soil layer was only 17.4%, which is 3.5% less than that of 1992. With 754 mm of rain in 1994, so soil water content recovered in 1995, increasing by 2% relative to 1994.

So soil water content in a 3 m soil depth changes markedly in spring for years with widely different rainfall ranges from 104 ~226 mm in 2 m soil layer and 149~298 mm in 3 m soil layer. On average, the saturation deficit is 172 mm in a 2 m soil depth, which is 76% of that of the saturation deficit in a 3 m soil depth, so we can conclude that 0~2 m soil layer plays a key role in soil intermediate storage. From Table 3, we can see the saturation deficit is 137 and 189 mm, respectively for 2 or 3 m soil depths at the end of spring.

5 Saturation deficit of soil reservoir in rainy season

5.1 Change of soil moisture before and after rain

There were 6 rainfall events during the period of 29th June to 13th July in 1994. Two were big storms and happened on 7th and 12th July, respectively. Rainfall was 46.9mm on 2nd and 3rd July, and from soil water content profiles it was possible to see that this precipitation and that of 29th June and 4th July was mainly stored in 0~1m soil layer. Then there were 3 rain events, 20.7mm on 5th and 116.6 mm in 7-8th. Water content in 0~1m soil layer had increased greatly by the 8th, rising from 21.0% on 5th to 29.2% on 8th, which was the biggest change in the recent years. Meantime, soil moisture content in 1~2m soil layer rose by 2% or so, showing that soil water could transfer quickly to deeper layers when the shallow soil was replenished by heavy rain. From field observation, soil water content increased by 8.0% in 0~3 m soil layer and there was hardly runoff after the 12th’s rainstorm. From well data, the water table was seen to quickly rise from 16.63 m to 15.22 m depth after the rains.

5.2 Effect on soil moisture content of years with widely different rainfall

Data was collected for several years to relate rainfall and soil water contents before and after the rainy season. From the data of Table 5, we can see that the rainfall in 1992 and 1993 is quite small and the soil water content after the rainy season is only 1.6% higher than that before the rainy season. While in 1994 and 1995, the increase after the rainy season was 4.7%, almost 3 times of that in 1992 and 1993. So the upper unsaturated layer of aeration zone gains a little benefit from a dry year’s rainy season; but in a heavy rainfall year, the layer is replenished much better.
Figure 2. Variation of soil water storage in rainy season of 1994

Table 5. Water additions in 0-3 m soil depth in rainy seasons

<table>
<thead>
<tr>
<th>Year</th>
<th>Before rain season</th>
<th>End of rain season</th>
<th>Rain season</th>
<th>Rain season</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Date</td>
<td>Average water content (%)</td>
<td>Date</td>
<td>Average water content (%)</td>
</tr>
<tr>
<td>1992</td>
<td>Mid June</td>
<td>22.4</td>
<td>First 10d in Oct</td>
<td>24.7</td>
</tr>
<tr>
<td>1993</td>
<td>First 10d in June</td>
<td>19.2</td>
<td>Last 10d in Sep</td>
<td>20.1</td>
</tr>
<tr>
<td>1994</td>
<td>First 10d in June</td>
<td>18.5</td>
<td>Last 10d in Sep</td>
<td>23.7</td>
</tr>
<tr>
<td>1995</td>
<td>Last 10d in May</td>
<td>19.4</td>
<td>Last 10d in Sep</td>
<td>23.6</td>
</tr>
</tbody>
</table>

References

Water-yield function of winter wheat and its application

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Abstract
In North China Plain (the Yellow-Huai-Hai Plain), per capita fresh water is less than 500 m\textsuperscript{3} per year, and about 7.7\% of the total available water is irrigating 39\% of the total farmlands and bringing up about 35\% of total population in China. Moreover, the ecosystems of this region have sacrificed significantly because the pumping of underground water in the areas is exceeding the recharge rate of aquifers. Many studies claimed that the development of a sustainable water supply for this region is an essential factor of the China’s food security and national economy. Agriculture in the North China Plain is very intensive, and winter wheat is a dominant crop that depends highly on irrigation. Great attention has been paid to improve irrigation water management for winter wheat production in this area aiming to increasing water and land productivity. Based on the field experiments at Chahezui Irrigation Experiment Station in Heilonggang, this paper presents the evapotranspiration (ET) of winter wheat and its changing pattern with different water supply, analyses the components of water consumption on-farm level and discusses the major influencing factors over ET of winter wheat. To avoid evident reduction of crop yields or other negative impacts resulting from the change of irrigation practices, the models of water production function (WPF) for winter wheat are carried out, and then, the optimum irrigation regimes for winter wheat in different hydrological years are suggested. These irrigation regimes concern the physiological and ecological water requirements of winter wheat, soil moisture and rainfall, and both irrigation depth and irrigation events may be reduced with surface irrigation. The case study shows that the recommended irrigation practices are feasible and simple for farmers to use.

Key words: Winter wheat; evapotranspiration; water-yield function; optimal irrigation program.

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1 Introduction
Per capita fresh water availability in China is among the lowest in the world and increasingly in short supply. The current debate over the ability of China to feed herself without importing massive quantities of cereals has centered on the water availability because the country-level data hide massive regional differences in water scarcity behind the average figures and the regional and seasonal water shortage is very serious (Brown and Halweil, 1998; DRWM, 2001; Qian and Zhang, 2001; Seckler et al., 1999; Serageldin, 1999). In the Yellow-Huai-Hai Plain, about 7.7\% of the total available water is irrigating 39\% of the total farmlands and bringing up about 35\% of total population in China. Per capita fresh water is less than 500 m\textsuperscript{3} per year, and it becomes one of the most water shortage regions in the world (Brown and Halweil, 1998; Heilig et al., 2000; Seckler et al, 1999). Moreover, the ecosystems of this region have sacrificed significantly because the pumping of underground water in the areas is exceeding the recharge rate of aquifers, so it should be considered to pay back the debt of ecologic water use. Nowadays, in Northwestern China, the ecologic and environmental conditions are deteriorating due to enlargement of irrigation system scales and over consumption of water resources (Brown, 1995; Brown and Halweil, 1998; Qian and Zhang, 2001).

In the North China Plain, cities are concentrated, industry is relatively developed, and population is dense. In the past, ecosystems and environment had been not in an advantageous position in competition of limited available water with other sectors. As a result, many rivers are often dried up, and groundwater table is falling. Dense population has led to much more intensive land use, which increases more water use. According to the national policy, Deficit irrigation should be used for the dominant crops wheat and maize which are very sensitive to water deficit (Pan, 2001), and priority will be given to this region for modernization of irrigation schemes and implementation of the agronomic and irrigation comprehensive measures (DRWM, 2001). Hence, great attention has been paid to improve irrigation water management for winter wheat production in this area aiming to increasing water and land productivity. Based on the field experiments at Chahezui Irrigation Experiment Station in Heilonggang, this paper presents the
evapotranspiration (ET) of winter wheat and its changing pattern with different water supply, analyses the components of water consumption on-farm level and discusses the major influencing factors over ET of winter wheat. To avoid evident reduction of crop yields or other negative impacts resulting from the change of irrigation practices, the models of water production function (WPF) for winter wheat are carried out, and then, the optimum irrigation regimes for winter wheat in different hydrological years are suggested.

2 Materials and methods

The field irrigation experiments of winter wheat were carried out at Chahezui Irrigation Experiment Station of Heilonggang district in the years of 1996-1997 and 1997-1998. The main water source in the irrigation region comes from Weihe run-off through the Chahezui water-lifting pump station. The average annual precipitation is 583.9mm and the mean groundwater depth is 13m from the surface. Full-time insolation is 2800 hrs, and accumulated daily temperature that is more than 5 °C reaches 4867.45 °C. Mean annual frost-free period is 197.3 d. The region is full of light and heat and fertile soil. Rain and heat come at the same time. So, the region is suitable for alimentary production.

In the irrigation experiments, single variable six levels (non-irrigation, 60mm, 120mm, 180mm, 240mm and 360mm) and two replications were employed and 11 experimental treatment plots were arranged, each being about 0.013ha. The method of oven-dried soil was used to measure the water requirements of winter wheat. Soil sampling was taken every five days and an additional test was made after rain. Quantitative fertilizing and similar field management measures were conducted in the experimental plots. The harvest of crop and the calculation of yields for individual plot were made separately. The self-recording rain gauge was used to record the rainfall. According to the analysis of long-series precipitation frequency, effective precipitation was analyzed to decide on the water production function of a hydrological year.

3 Winter wheat water requirements

Table 1 gives values of measured ET from 11 plots, and the changing patterns of daily ET of typical treatments are shown in Figure 1.

<table>
<thead>
<tr>
<th>Growth stage</th>
<th>Revival of green</th>
<th>Booting</th>
<th>Shooting</th>
<th>Milk ripening</th>
<th>Full ripening</th>
<th>Whole season</th>
<th>Yields (kg/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Days</td>
<td>140</td>
<td>31</td>
<td>21</td>
<td>19</td>
<td>21</td>
<td>232</td>
<td></td>
</tr>
<tr>
<td>TR1</td>
<td>27.4</td>
<td>32.7</td>
<td>28.4</td>
<td>33.8</td>
<td>66.5</td>
<td>188.8</td>
<td>1763</td>
</tr>
<tr>
<td>TR2</td>
<td>86.7</td>
<td>34.9</td>
<td>43.9</td>
<td>43.9</td>
<td>42.8</td>
<td>268.5</td>
<td>2363</td>
</tr>
<tr>
<td>TR3</td>
<td>110.7</td>
<td>65.4</td>
<td>79.9</td>
<td>55.1</td>
<td>80.6</td>
<td>391.5</td>
<td>4425</td>
</tr>
<tr>
<td>TR4</td>
<td>98.7</td>
<td>51.9</td>
<td>107.8</td>
<td>87.2</td>
<td>117.9</td>
<td>598.7</td>
<td>6675</td>
</tr>
<tr>
<td>TR5</td>
<td>95.6</td>
<td>64.5</td>
<td>89.3</td>
<td>50.1</td>
<td>82.5</td>
<td>382.4</td>
<td>5325</td>
</tr>
<tr>
<td>TR6</td>
<td>91.8</td>
<td>51.6</td>
<td>99.7</td>
<td>52.1</td>
<td>79.1</td>
<td>378.5</td>
<td>5213</td>
</tr>
<tr>
<td>TR7</td>
<td>61.5</td>
<td>50.4</td>
<td>48.3</td>
<td>51.1</td>
<td>103.8</td>
<td>314.9</td>
<td>4688</td>
</tr>
<tr>
<td>TR8</td>
<td>110.5</td>
<td>69.6</td>
<td>46.4</td>
<td>48.7</td>
<td>66.1</td>
<td>339.8</td>
<td>5775</td>
</tr>
<tr>
<td>TR9</td>
<td>96.5</td>
<td>50.9</td>
<td>36.4</td>
<td>47.3</td>
<td>103.9</td>
<td>320.7</td>
<td>4838</td>
</tr>
<tr>
<td>TR10</td>
<td>122.2</td>
<td>97.4</td>
<td>70.7</td>
<td>49.1</td>
<td>90.2</td>
<td>429.4</td>
<td>6075</td>
</tr>
<tr>
<td>TR11</td>
<td>105.3</td>
<td>54.4</td>
<td>36.8</td>
<td>30.2</td>
<td>42.9</td>
<td>329.7</td>
<td>5700</td>
</tr>
</tbody>
</table>

![Figure 1. Changing patterns of daily ET of winter wheat](image-url)
From Table 1 and the Figure 1, ET of the whole growth season of winter wheat changes from 188.8 mm to 463.7 mm with different water supply. For the same irrigation treatment, it changes noticeably in different growth stages. Despite the long time before booting, the values of ET are quite small because the leaf area index is small and temperature is low. Water requirement is highest in shooting and milk ripening stages. Winter wheat is the most sensitive to water around the shooting and flowering period for both exuberant reproductive and vegetative growth, ET reaches a daily 5~6 mm maximum value.

As irrigation is not always available in the North China Plain, changes of soil moisture in winter wheat growth season should be considered. The water storage function of root zone plays an important role in alleviating drought resulting from uneven rainfall distribution. Normally, there is a greater change in field soil moisture content in the development stage of winter wheat because it is very dry in spring in this region. Without sufficient winter irrigation, very low soil moisture might result in spring. If soil moisture could be as high as 70% of field capacity, then water requirements of winter wheat at the development stage could be met without more water being supplied.

4 Water production function of winter wheat

4.1 Irrigation production function of winter wheat

Equation 1 is obtained based on the modeling of values from 11 treatments.

\[ y = (-34.48 \times 10^{-3})x^2 - 27.46x + 640.704 \quad (1) \]

where \( y \) is the yield of winter wheat (kg/ha); \( x \) is the irrigation depth (mm).

The irrigation production function variance is 0.300 and the coefficient of multiple correlations is 0.8312.

4.2 Water production function of winter wheat

For the Blank Model, WPF of winter wheat can be described as:

\[
F \times \frac{y}{y_m} \times \max \sum A_i \frac{ET_a}{ET_m} \frac{y}{y_m} \\end{align}
\]

\[ 0.00257ET_{a1} \times 0.00598ET_{a2} \times 0.0264ET_{a3} \times 0.00224ET_{a4} \times 0.00148ET_{a5} \]

where \( A_i \) is the water deficit coefficient at stage \( i \); \( ET_a \) is the actual ET of winter wheat at stage \( i \) (mm); \( ET_m \) is the maximum or potential ET of winter wheat at stage \( i \) (mm); \( Y_a \) is the actual yield of each treatment (kg/ha); and \( Y_m \) is maximum or potential yield of winter wheat (kg/ha).

4.3 Annual winter wheat water consumption

Based on the analysis of the measured data (137 samples and 12 years) of the water consumption and yield of winter wheat from the irrigation experimental station in Heilonggang district, the annual water consumption function of winter wheat is expressed as:

\[ y = (-30.61 \times 10^{-3}) \beta - 29.71 \beta - 1 825.38 \quad (3) \]

where \( \beta \) is the annual water consumption of winter wheat (mm).

The water consumption function variance is 35.41 and the coefficient of multiple correlation is 0.8312.

5 Optimal irrigation model for winter wheat

5.1 Construction of optimal irrigation dynamic model of winter wheat

5.1.1 Stage variables

The whole growth season is divided into 5 stages, and the two-dimension dynamic programming is used to determine the optimal dynamic model of the irrigation program, which is constructed with the goal of maximum yield. The stage variables are numbered in sequence in the natural growing periods, i.e., planting to revival of crop, revival to booting, booting to shooting and flowering, flowering to milk ripening and milk ripening to full ripening, and \( n = 1,2,3,4,5 \).

5.1.2 Decision variables

Decision variables mean the irrigation depth of each growing stage, \( m_i \).

5.1.3 State variables

There are two state variables; available water \( q_i \) for allocation at the beginning of each growth phase and the available water in root zone decided by the soil moisture content \( w_i \). \( w_i \) can be estimated from:

\[ W_i \times 10^{-6} H \theta \]

where \( y \) is the soil unit weight; \( H \) is the rooting depth for a given crop at stage \( i \) (m); \( \theta \) is the mean soil moisture content of rooting depth at the same time (%); \( w \) is the lower limit soil moisture content (%).

5.1.4 Systematic equation

Two systematic equations are the water allocation equation and the water balance equation. Those are:

\[ q_{i+1} \times q_i \times \frac{m_i}{m_i} \]

\[ W_{i+1} \times W_i \times P_i \times m_i \times ET_{al} \]

(5)
where \( q_i \) and \( q_{i+1} \) are the available water for allocation at stage \( i \) and stage \( i+1 \) respectively (mm); \( W_i \) and \( W_{i+1} \) are available water in rooting zone at stage \( i \) and stage \( i+1 \) respectively (mm); \( P_i \) is the effective precipitation at stage \( i \) (mm); \( ET_{ai} \) is the actual evapotranspiration of winter wheat at stage \( i \) (mm).

5.1.5 Objective equation

The objective is to get maximum yield for a given water quantity. That is:

\[
F \Rightarrow \max \frac{y_a}{y_m} = \max \left\{ A \frac{ET_a}{ET_m} \right\}
\]

5.1.6 Restraining conditions

Decision restricting conditions are:

\[
i ? m_i \leq q_{i+1} \leq 5 \]

\[
i ? m_i \leq 5
\]

Soil moisture content restraining conditions are:

\[
W_{min} \leq W_i \leq W_{max} \quad \text{for} \quad i \in \{1, 2, 3, 4, 5\}
\]

5.1.7 Initial status

Available soil water in the fields at the beginning of the season is:

\[
W_0 \leq 10H
\]

where \( W_0 \) is the initial available soil water (mm). The water for allocation at the beginning of the irrigation season is the total available water for winter wheat. That is: \( q_i = Q \)

5.2 Calculation of effective precipitation

Measured data is used to estimate the effective precipitation for winter wheat. As the soil moisture content was always lower that the field capacity, the available rainfall is the difference of soil water content before and after rainfall.

\[
P_0 = \gamma H (\theta /c_1 - \theta /c_2)
\]

5.3 Optimal irrigation model for winter wheat

From status equation and objective equation, a recurrence equation of the model is obtained as follows:

\[
f^* (q_{i+1}, w_{i+1}) = \max \left\{ A \frac{ET_a}{ET_m} \right\}
\]

\[
\text{for} \quad i = 1, 2, 3, 4, 5
\]

5.4 Implementation of the model

The basic information from Chahezui is given in Table 2, and results of modeling are shown in Table 3.

### Table 2. Basic information for modeling

<table>
<thead>
<tr>
<th>Items</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.169</td>
<td>0.207</td>
<td>0.189</td>
<td>0.130</td>
<td>0.116</td>
</tr>
<tr>
<td>ETm</td>
<td>65.77</td>
<td>34.65</td>
<td>71.89</td>
<td>58.14</td>
<td>78.66</td>
</tr>
<tr>
<td>P</td>
<td>9.41</td>
<td>4.40</td>
<td>17.41</td>
<td>21.34</td>
<td>12.07</td>
</tr>
</tbody>
</table>

### Table 3. Optimal allocation of available water for irrigation (mm)

<table>
<thead>
<tr>
<th>Total available water</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>y_a / y_m</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.346</td>
</tr>
<tr>
<td>75</td>
<td>75</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.642</td>
</tr>
<tr>
<td>150</td>
<td>75</td>
<td>75</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.774</td>
</tr>
<tr>
<td>225</td>
<td>75</td>
<td>75</td>
<td>75</td>
<td>0</td>
<td>0</td>
<td>0.903</td>
</tr>
<tr>
<td>300</td>
<td>75</td>
<td>75</td>
<td>75</td>
<td>75</td>
<td>0</td>
<td>0.906</td>
</tr>
<tr>
<td>375</td>
<td>75</td>
<td>75</td>
<td>75</td>
<td>75</td>
<td>75</td>
<td>0.939</td>
</tr>
</tbody>
</table>

The objective function of this model includes the influence of coefficient A that has been got from the measured data. The results in Table 3 show the model is feasible.

### 6 Conclusions

The proposed irrigation regime for winter wheat includes irrigation before planting, before freezing season and during booting stage, with depths of 90mm, 60mm and 60mm respectively. Proposals are based on available water for winter wheat in the Chahezui irrigation area, using an optimum irrigation model for winter wheat for 50% probable rainfall. For only 75% probable rain, the suggested irrigation regime for winter wheat includes irrigation before planting, before freezing
season, during booting stage and shooting and flowering stage, and the irrigation depths are 90, 90, 60 and 60mm, respectively. The case study and the implementation indicate that the model is feasible.

References
Study on the dynamic mechanism of sheet flow in soil erosion chain in loess area

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Abstract
By simulated rainfall experiments, the process of sheet flow in soil erosion chain in Loess Hilly Area was studied, and the results showed that the flow velocity-discharge, the friction factor-Reynolds number (Re) and the Froude number (Fr)-Re were all in power functional relations. Except the friction factor–Re relation decreased progressively and monotonously, the other two both increased successively and monotonously. The sheet flow produced by rainfall, which is unstable and uneven in the temporal and spatial distribution, is not the typical laminar flow, but the heavily-disturbed turbulent flow affected by rainfall and underlying surface, which with the characteristics of torrent. The above characteristic of sheet flow is the real and primary factor to cause the erosion. The study was of profoundly theoretical significance to discovering the rules of sediment yield by slope erosion.

Key words: soil erosion chain, sheet flow; hydraulic parameters; dynamic mechanism

Hilly slope and gully slope are closely related and form an open and dynamic system in Loess Hilly Area. The rainfall is the input or stimulating variable, the runoff and sediment are the output or state variables, and natural conditions and human activities, which influence the temporal and spatial variation of the output and the input to some degree, form the external environment. There is a particular connection among the erosion substance, the erosion energy and the erosion type, which is affected by the mutual effects of erosion power and anti-erosion power and linked by the flow of erosion energy, and they integrate organically through the evolving chain structure in which the erosion types correlate mutually and are arranged orderly, which is characterized by the transfers and outputs of erosion substance and is called the erosion chain.

In the erosion chain, water flow is continuous at the transition from one erosion type to another, but there is a sudden change of its dynamic characteristics, which is expressed by dynamic criticality. The criticality is an important standard to distinguish the erosion types and to categorize the hydraulic science. The dynamics mechanism of both sheet flow and rill runoff are discussed in the paper.

1 Materials and methods
Experimental model is composed of experimental soil box and angle steel experiment frame, the grade of which can be adjusted from 0 ° to 25° . The size of the soil box is 1.5 m×1.0 m×0.4 m which is marked on both sides at set length ( 5 cm~10 cm ) in red and white. The sides of the soil box are made inclined in order to reduce the effects (produced by the board) on the rainfall. At the bottom of the box, small holes (d=5mm) are scattered into the plum blossom shape in order to eliminate the effect on soil infiltration by lateral conditions. The experimental soil is loess soil, its mechanical composition is: 0.12% (1mm) 0.25 mm ), 2.70% (0.25mm) 0.05 mm ), 41.13% (0.05mm) 0.01 mm), 6.88% (0.01mm) 0.005 mm ), 12.89% (0.005mm) 0.001 mm), 36.28% (0.001mm), 56.05% (0.01mm). The experimental soil is sieved (d=10mm), soil density ( ) is 1.20 g/cm³, and soil water content ( ) is 15%. The selected rainfall intensity is 29.7 mm/h, 90.2 mm/h and 153.7 mm/h respectively. The selected grades are 5 °, 10°, 20° and 25° respectively. The simulated rainfall and scouring are both adopted in experiments to simulate the variation of the slope length. The amount of water discharge is decided on the measured amount and flow speed after the stable runoff formation produced in the former rainfall. Each rainfall process lasts 60min. During the experiment, the runoff velocity, the runoff depth, the sediment content and the runoff discharge are observed and recorded every other 5 minutes after the runoff appears. The sediment is dried to get the erosion amount. The flow velocity is got by the dye method, and the flow depth is calculated through the flow discharge and velocity. The period and amount of runoff formation are measured after the rainfall.
Results and Analysis
The sheet flow refers to two types of flow: (1) the small shallow and dispersed sheet runoff produced before the rills emerge on the slope when the rainfall intensity is greater than the soil infiltration capacity; (2) the runoff flowing among the rills after the rills have emerged flows broad along the slope. The sheet flow is often shallow and affected by the rainfall and slope roughness greatly, and the boundary conditions are complicated. In comparison with the general free flow, the sheet flow has its distinct hydraulic characteristics. They are determined primarily by two factors: the rainfall and the underlying surface. The former factor refers to rainfall intensity, rain type and the duration of rainfall, and the latter includes soil composition, the previous moisture content, density and type of the vegetations, grade and length of the slope and so on.

1. Relations among the main hydraulic parameters of the sheet flow
According to the experimental data, the relations of the discharge-velocity, the friction factor-Re and the Fr-Re are established by the correlation analysis. The experiential equations of each relation are expressed in Table 1.

<table>
<thead>
<tr>
<th>Correlation Parameters</th>
<th>Condition</th>
<th>Experimental equation</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity and discharge</td>
<td>$V=36.7q^{0.37}$</td>
<td>0.843</td>
<td></td>
</tr>
<tr>
<td>$q$</td>
<td>$V=51.4q^{0.38}$</td>
<td>0.832</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$V=68.1q^{0.59}$</td>
<td>0.811</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$V=38.2q^{0.37}$</td>
<td>0.820</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$V=28.0q^{0.36}$</td>
<td>0.793</td>
<td></td>
</tr>
<tr>
<td>friction factor-Re</td>
<td>$F=2.600R^{-0.716}$</td>
<td>0.836</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$F=4.298R^{-0.743}$</td>
<td>0.829</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$F=4.777R^{-0.786}$</td>
<td>0.813</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$F=4.773R^{-0.716}$</td>
<td>0.801</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$F=11.432R^{-0.677}$</td>
<td>0.799</td>
<td></td>
</tr>
<tr>
<td>Fr - Re</td>
<td>$Fr=0.268R^{-0.738}$</td>
<td>0.837</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$Fr=0.282R^{-0.740}$</td>
<td>0.831</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$Fr=0.298R^{-0.768}$</td>
<td>0.793</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$Fr=0.300R^{-0.717}$</td>
<td>0.814</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$Fr=0.190R^{-0.673}$</td>
<td>0.805</td>
<td></td>
</tr>
</tbody>
</table>

Just as Table 1 showed, that the three relations are all power functional relations and except the friction factor-Re relation, which decreases progressively and monotonously, the other two relations increase progressively and monotonously. The velocity-discharge relation indicates that the velocity of sheet flow increases as the discharge flow grows, and its amplitude changes with the rainfall intensity and grade. And that at the set rainfall intensity, the higher the grade is, the greater the amplitude is; at the same grade, the greater the rainfall intensity is, the lower the amplitude is. For the same discharge, the higher the grade is, the lower the velocity is and the greater the rainfall intensity is, the greater the friction factor too. The reason why the friction factor grows with the increase of grade is that the velocity increases as the grade increases, since the rainfall area is fixed, the increase of velocity naturally cause the lower runoff depth correspondingly, thus leading to a relative growth of the slope roughness which increases the friction factor to some extent. What the rainfall intensity increases the friction factor for is that the rainfall brings about a certain “soft boundary” on the slope surface which can cause the drag force. The soft boundary increases the drag force primarily by two kinds of effects. One kind of effect is that the continuous beats of raindrops destroy the stability of the runoff surface and directly result in the undulant movement, thus making the flow distance longer and causing the additional drag force. The other kind is that the continuous beats of raindrops bring about a disorderly mixed flow near the soft boundary, thus increasing the stress and the current drag force. However, the rainfall intensity determines the above two kinds of effects and restricts the current drag force.

The Fr is an increasing function of Re and increases with the growth of Re. At the same rainfall intensity, the higher the grade is, the greater the increase scope of Fr is; and at the same
grade, the greater the rainfall intensity is, the smaller the increase scope of Fr is. However, for the same Re, the higher the grade is, the bigger the Fr is and the greater the rainfall intensity is, the smaller the Fr is. The reason why the grade can increase the Fr is that the runoff velocity grows as the grade increases and the runoff depth becomes lower correspondingly, thus resulting in an evident growth of the Fr. The growth of the Fr at steeper grade changes the partial slope friction and forms a section of torrent on the slope, which leads to the formation of numerous tiny step pond and develops the uneven runoff to a more serious state. Since the flow ejection and the severe scouring often appears under that condition, the bumps and roughness on the slope grow more evident and act on the flowing runoff in turn, which urges the torrent to develop further and accelerate the slope erosion. The effects on the partial fraction produced by rainfall intensity can be analyzed from two aspects. One is that the rainfall disturbs the sheet flow and the runoff velocity at greater rainfall intensity becomes lower instead, so the runoff depth increases correspondingly and the Fr is small naturally. The other is that the rainfall brings about the badly-distributed undulations and uneven depth of sheet flow, and the greater the rainfall intensity is, the more notable this effect produced by it. Large raindrops lead to obvious splash erosion puddles and spotted stains of rain, which are both the embryonic forms of those tiny step pond on the slope and may result in torrent if developing further.

2.2 Type and Characteristics of sheet flow

As we know, when the Re is greater than 580, the flow is turbulent flow and when less than 580, the flow is laminar flow. The sheet flow is basically categorized into the laminar flow. However, its Re increases gradually along the slope surface. Even so, the Re of sheet flow does not increase infinitely. The rill erosion will be caused if the runoff velocity and depth increase to certain extent when the sheet flow has accumulated a considerable quantity of turbulent energy. Although there still is sheet flow flowing among the rills, its velocity and depth will no longer increase evidently and its Re is consequently limited in a certain scope. According to the measured results, it is nearly not exceptional that the sheet flow becomes a turbulent flow before the Re goes beyond the critical 580. Then the question comes: what accounts for the erosive effects of the sheet flow? There are three specific characteristics of sheet flow as follows:

2.2.1 Sheet flow is unstable and uneven in the temporal and spatial distribution

At each set point in the fluid field, the runoff velocity and other hydraulic parameters vary along the flow distance, and the velocity and depth of the runoff aren’t well-distributed. This phenomenon has a bearing on the temporal and spatial distribution of many factors, such as rainfall, microlandform and infiltration etc. Affected by these factors, when rains, the runoff depth changes constantly, the flow route gets complicated and some phenomena, such as the crosswise mixing and wave etc., appear frequently, which is one reason for the turbulence and erosion resulted from the sheet flow.

2.2.2 The sheet flow is a heavily-disturbed turbulent flow

The rainfall increases the turbulence of sheet flow mainly by two ways. The direct way is that the rainfall splashes the soil granule and mud and carries them to the down slope, which directly supplies the sheet flow with the necessary substance to produce erosion. The second way, which is relatively indirect, primarily includes three kinds of effects: (1) Beating the runoff surface or even directly penetrating the runoff by the rainfall cause the splash erosion pits on the slope, which strengthen the erosion capacity of the sheet flow. (2) The disturbed runoff continuously stirs, turns and carries the loose materials flowing forwards along the slope, thus increasing the turbulence of sheet flow. (3) The rainfall with greater rainfall intensity may also cause waves on the runoff surface and the waves disperse, push and collide with each other, thus resulting in the growth of turbulence and transport capacity of the sheet flow. Underlying surface acts on the sheet flow mainly through the roughness. Even if the ground is very flat, the bump and roughness will also be caused after the rainfall. The protruding parts of those bumps are often high above the water surface and result in the complex flowing of the sheet flow.

2.2.3 The torrent is also an important factor influencing the sediment production and transport capacity of sheet flow.

By observations and measurement, the sheet flow becomes typical of torrent as soon as the runoff appears at the rainfall intensity of 29.7mm/h. It develops unceasingly and causes numerous tiny step pond on the slope, which makes the uneven bump and roughness more obvious. influence and promote mutually and the erosion process gets more and more serious, thus creating conditions for the rill erosion continuously. The velocity-discharge relation of sheet flow is \( v \propto q^{0.56-0.59} \) and the velocity-depth relation is \( v = h^{1.273-1.439} \). The exponents in the above relations are different from those of both the laminar flow and the turbulent flow, and situate between them instead. Since the runoff is also typical of torrent, it is called rushing laminar flow.

2.3 Characteristics of sediment yield of sheet flow

Based on the experimental data, the processes
of runoff formation and sediment yield of sheet flow are depicted as follows. The process of runoff formation is that the runoff gradually grows until it tends to be stable after the peak value. The processes of runoff formation at different rainfall intensity are dissimilar evidently and the greater the rainfall intensity is, the greater the amount of runoff formation is. However the differences of runoff formation process at various grades are not obvious. Although the higher grade takes effects on increasing the velocity and decreasing the infiltration, it decreases the area of current convergence, which counteracts the effects and results in the invident difference among the processes of runoff formation caused by grade.

The process of sediment yield is relatively complex and typical of peaks and valleys. At the beginning of runoff formation, the soil moisture is low and the soil particles are loose and it is easy for the soil to be separated by the splash erosion, so the first crest value appears soon. However, the runoff amount is often small and there is some time to go before the next crest of runoff formation, therefore, the sediment yield rapidly decreases and the valley value appears after the first peak of sediment yield. With the extension of rainfall, the runoff grows and the scouring capacity increases gradually until the runoff formation is approached to the peak value, and the second crest in the process of sediment yield possibly appears then. Henceforth, the process of sediment yield becomes steady as the runoff formation gradually gets stable. The processes of sediment yield and runoff formation, with high sediment and large runoff, are in correspondence with each other. At the same grade, the greater the rainfall intensity is, the greater the sediment yield and runoff amount are. Because of the little difference among the runoff formation at various grades, the distinctness of the sediment yield processes at various grades is difficult to distinguish in the figure. To understand the characteristics of sediment yield at various gradients and rainfall intensity, the average sediment yield per unit discharge flow of each rainfall is calculated and listed in Table 2. For the sheet flow, the erosion is positively correlated to the rainfall intensity and the grade, but the rainfall intensity takes much greater effects on the erosion than the grade. The sediment yield grows basically in an arithmetic progression as the grade increases, while it increases generally in a geometrical progression as the rainfall intensity grows.

<table>
<thead>
<tr>
<th>Rainfall intensity (mm/h)</th>
<th>grade(°)</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.7</td>
<td></td>
<td>7.85</td>
<td>8.685</td>
<td>9.484</td>
<td>10.54</td>
<td>12.50</td>
</tr>
<tr>
<td>90.2</td>
<td></td>
<td>20.82</td>
<td>22.35</td>
<td>23.50</td>
<td>24.80</td>
<td>26.70</td>
</tr>
<tr>
<td>153.7</td>
<td></td>
<td>58.95</td>
<td>60.10</td>
<td>62.10</td>
<td>63.30</td>
<td>63.14</td>
</tr>
</tbody>
</table>

At the same grade, the discharge grows substantially as the rainfall intensity becomes greater, and the runoff velocity and depth increase correspondingly. Although the rainfall intensity plays a role in lowering the velocity, it increases with the discharge growth and its increment is merely a little lower than that of the depth. As the velocity and depth grow, the runoff turbulence grows great, the drag force decreases along the flow distance, the effects on scouring and separating the soil become obvious, and the sediment transport capacity increases, which is the reason for the rapid growth of sediment yield at great rainfall intensity. At the same rainfall intensity, the area of receiving rainfall decreases 10 percent when the grade varies from 5° to 25°. Although the velocity grows a little when the grade increases, the growth is almost counteracted...
by the shortened flow distance caused by the growth of grade. Meanwhile, since the depth decreases correspondingly, the $Re$ grows or even decreases to a certain extent. Despite the $Fr$ grows, the increment is much less than that caused by the growth of rainfall intensity. Therefore, the increment of sediment yield is not remarkable when the grade increases.

3 Conclusions

For the sheet flow, the relation of the flow velocity-discharge, the friction factor-$Re$ and the $Fr$-$Re$ are all power functional relations; and except the friction factor-$Re$ relation, which decreases progressively and monotonously, the other two relations both increase successively and monotonously. Grade plays a role in increasing the velocity and reducing the runoff depth, while rainfall intensity takes effects on decreasing the velocity and raising the runoff depth. Both grade and rainfall intensity take effects on increasing the drag force of runoff; grade causes the $Fr$ to grow, while rainfall intensity makes it reduced.

The sheet flow produced by rainfall, which is unstable and uneven in the temporal and spatial distribution, is not the typical laminar flow but the heavily-disturbed turbulent flow affected by rainfall and underlying surface, which is typical of torrent. On grounds of two experiential relationships (the discharge-velocity relation and the discharge-depth relation), the sheet flow is dissimilar with the laminar flow and the turbulent flow, but situates between them. The above characteristic of sheet flow is the real and primary factor to cause the slope erosion.

References


Better use and control of rainwater in Beijing’s City development

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Abstract
With the development of Beijing City there are two contradictory water resource problems. A shortage of water is combined with increased flood risk, arising from rapid runoff from paved areas. Traditional sunken swales can store rainwater, aid rainwater infiltration, ultimately improve local groundwater quality and perhaps reduce local demand from piped services. At the same time the load on city sewers is reduced, as is the flood risk for lower reaches of local rivers. It is hoped that recommendations might be brought to the attention of city planners and builders, thereby enhancing the city’s beauty.

Key words: City development; controlling runoff and sunken lawns.

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1 Introduction

1.1 Water supply
Many parts of China have inadequate water resources with nearly 400 of the 700 cities having serious water shortage problems. Beijing has become one of the large cities that is short of water. Since the middle of 1980s, Beijing has depended on excessively mining groundwater to temporarily keep the balance between supply and demand. The water overdraft amounts to almost 4 billion m$^3$. As a result, the regional cone of ground water depression beneath the city was estimated to be as much as 1000 sq. km. As aquifers become nearly empty, ground subsidence occurs and groundwater quality deteriorates if salt-water intrusion takes place.

1.2 Pollution
Uncontrolled water pollution can cause nuisance odors along canals and rivers. Another water pollution related problem is serious siltation in rivers and lakes. Impact of the surface water pollution on groundwater quality becomes more significant as the groundwater dries up. Measures has been taken in Beijing for pollution control such as rivers desiltation and dredging, sewage closure, tree and grass planting, improving the structure of fuel, regulating vehicle exhaustion and so on. All of the measures are related and thus can impact each other. For instance, an increase in city areas relying solely on tap water irrigation certainly will aggravate the water resources stress again.

1.3 Demand management
Many northern cities in China have begun to limit the time for supplying water. One has to consider both conservation and resource enhancement so that Beijing can continue to regulate water supply and does not have to limit water supply time as in some other cities.

2 Current problems

2.1 Runoff phenomena
Flooding is a real threat in Beijing. As urbanization develops, the extent of impervious land area increases. Consequently, the amount of runoff increases. Rainfall runoff hydrographs of are high and narrow, since 80% of North China’s rainfall is concentrated in the flood season from 15th June to 15th September and a higher degree of concentration occurs in a wet year. Improvement of the sewerage system of downtown districts has made it possible for stormwater to flow quickly into sewer drains, thus adding to the burden of lower reaches of a river in controlling flooding.

Statistical data for 1961 to 1983, shows that the mean runoff outflow rate was 950 million m$^3$ during the flood season. During the typical low precipitation years between 1980 and 1986, runoff amounted to 120 -190 million m$^3$ during the flood season. In 1986, the city’s annual average precipitation was 560 mm, which corresponds to a middle to low rainfall year. Then, runoff was about 460 million m$^3$.

2.2 Limitations of flood flow network
In addition, with the great numbers of high buildings standing on both sides of rivers in the downtown district, some rivers have been converted to culverts, which makes it more difficult to widen river sections and increase the flood control capabilities. So some downstream sections have inadequate capacity for flood control and little room is available for further
broadening the river channels. Not only do infrequent rainstorms produce inundation of large areas within the city limits, but also even regular rainstorms can create ponding in some local areas. Clearly, Beijing city faces a double threat of lack of water resource along with inundation within the city and floods in downstream river areas. Adopting measures that increase rainwater storage and infiltration offers an economical and effective option for mitigating the risks during city expansion.

3 Current solutions
3.1 Introduction
There is a variety of existing flood control measures. Firstly flood runoff can be accommodated in natural lakes, ponds, reservoirs and ditches, specifically identified for flood detention. A second measure in the Beijing water plan is to construct artificial impounding ponds. Such structures are complicated, have high costs and need consider the prevention of contamination when dammed floodwater is used as a water resource. They are generally considered to be not suitable for Beijing, as the annual rainfall is about 600mm with only 15~20 days having daily rainfalls above 10mm\(^{[1]}\). Consequently, the efficiency of using impounding ponds is low considering the high cost of construction. Systems can be also constructed to recharge groundwater through artificial recharge. The key question is water quality. This type of system must not only guarantee recharged water quality, but also have relatively simple structures. So this measures deserves further research.

Other localized measures to impound rainwater include using a sunken greenbelt, storage and infiltration wells, storing and infiltration swales and paving ground with pervious materials. These measures are suitable for use in Beijing, with the city being located in an outwash deposit area formed by the Yongding and Chaobai rivers. So soils have good water permeability and there are also large underground reservoirs with plentiful sandstone to backfill constructed infiltration wells and infiltration swales. The quality of rainwater recharging the groundwater should be guaranteed, since soils and greenbelts have filtering and purifying functions.

3.2 Sunken greenbelt/grass belt
The sunken greenbelt alters the conventional way of improving a city development or layout of the yard. The greenbelt should be constructed lower than the road and the gully should be located in the greenbelt. Its ridge should taller than the greenbelt but lower than the road. Runoff from roofs, roads and the lay areas should first flow into the grass belt, and then drain into rainwater pipes from the gully through storing-infiltration function of grass belt. Storing-infiltration wells and storing-infiltration swales should be constructed in the small grass belt area; within existing districts, there are difficulties in rebuilding facilities according to new standards. High cost makes it impractical. But similar means can be considered such as to enclosed grass belts with barriers, and forming sunken greenbelts. Such a structure can collect rainwater and flood (such as runoff of rainwater pipe) of the surrounding area near a grass belt. An overflow port is constructed at proper position to drain the redundant rainwater to an existing gully.
The sunken greenbelt is a measure to use rain-flood water, which doesn’t increase the construction cost but has beneficial effects. One of the major advantages is that it reduces the flood-water logging disasters and increases runoff filtration and groundwater recharge, cutting down irrigation water requirement of the grass belt. Another advantage is that it can reduce sewage, silt and nutrient runoff into surface water, thus protecting the water quantity of rivers and increasing the soil fertility of grass belt. The sunken greenbelt itself in this case is a settling basin and a land treatment system of sewage; the third advantage is that gully is laid within the grass belt, which beautifies the road.

3.3 Pervious paving
Pervious material is a kind of paving structure that allows water percolation. There are two types of shape, one with holes and the other without. Grass can be planted with the type that has holes. With the increased understanding to beautify environments and to utilize the rainfall resource, the use of pervious material has gained more popularity. Pervious material is usually used in footpaths, stopping places, parks and tree shade shelterbelts. Compared with impervious material, one of the advantages is that the water permeability ground laid with pervious material is not reduced, which still store rainwater, recharge groundwater, conserve water resource, reduce water requirement and makeup groundwater. The second advantage is that it can increase the area of grass belt in city, reduce the surface temperature, humidify and purify air, reduce dust. Through the measures we can improve the living environment and enhance the environment quality. The third advantage is that with the increase in car numbers, after paving the park with grass belt, then some parking problems may be resolved. The fourth advantage is that laying pervious material has the capacity of protecting parts of grass belts used as walkways and tree planting areas in parks, by keeping soil
loose of soil to avoid damaged grass due to pedestrians. Pervious material is laid in parks for walking and exercise. It prevents soil compaction and promotes the growth of tree roots. The fifth advantage is that the covering material for lawns can be also used for parking, which displaces the image of all parking lots being made of asphalt.

3.4 Technical problems
The sunken greenbelt, infiltration swales, infiltration wells and pervious material are favorable to sustainable development of city, but someone may put forward the questions, for instance, whether the grass would be die as a consequence of extended submergence in water. The answer is unlikely. Due Beijing’s soil texture being generally silty soil (the constant infiltration index is 100-300mm/d), so it should not pond under the typical rainfall conditions during flooding seasons. Even with the maximum daily rainfall (201-259mm), the grass will not be submerged to a depth of 15cm for two days. Cotton grass, along with nine other types of grass, has been tested for resistance to flood conditions. Experimental conditions included air temperatures of 11-31°C, water temperatures of 14-25.5 °C, and a flooding depth of 15cm. Reaction to two, four and six days of soaking was examined. Growth conditions were observed after separating the grass from flooding environment of 14 days, and compared the flood tolerance of grass under the condition of the normal growth as standard. Results showed that the flood tolerant days for nine types of grass were two days; the flood tolerance of seven types of grass was four days; the flood tolerance of four types of grass was six days. The flood tolerance of cotton grass, buffalo grass, high couch grass and low spear grass is much better. The growth of these grasses typically cannot be affected by temporary flooding. The grasses can maintain the landscape under the condition of rainstorms.

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Study on rainwater and fertilizer pit-storing technique in apple orchard in the ravine and gully area of the highland

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Abstract
Eight apple-production methods were compared while trees were fruiting. The surroundings of individual apple tree can serve as rainfall collection units that assist in storing water beneath a zero-till surface. Either no irrigation or only slight irrigation is required in an average year. Compared with clean tillage, the pit-growing technique can promote a 9.4-21.7% increase in gravimetric surface soil water. It is judged to be an effective water saving measure for apple production in the gullied highland areas.

Key words: Ravine and gully areas, apple orchard, pit-storing fertilizer and water, rain collection, water use efficiency

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1 Introduction
Growing apples makes good use of ravines and gullied areas but limited and uneven annual rainfall restricts apple yield, with potential limitations on quality and economic benefit. For these reasons, water-saving irrigation together with soil and water conservation practices are promoted to reduce evaporation and to fully use natural precipitation. Dongzhi Farm, Xifeng Supervisory Bureau for Soil and Water Conservation of the Huanghe River is located in such an area. Annual average precipitation is 561.5mm compared with an annual evaporation capacity of 1,527mm. Soils on the farm are deep and have a mature, black, open structure with field capacity values of 27g/kg. The area of its apple orchard is 5.7 ha and the main variety of apple grown is “Red Fuji”. This is now in the fruit-bearing stage and acts as a demonstration base for producing high-quality apples. Research is carried out on water-saving irrigation, zero tillage with mulching, concentrated fertility treatments and water use efficiency. Related practices are significant during intensive apple growth. Many factorial experiments have been conducted here and brought about remarkable social and economic benefits.

2 Materials and methods

| Table 1. Combination of the hole-storing fertility and water and the rain collection |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| treatment                      | mulch covering (A)              | straw covering (B)              | weed covering (C)              | clean tillage (D)              |
| hole-storing fertility +       | AF                              | BF                              | CF                              | DF(ck)                         |
| tree shed water collection     |                                 |                                 |                                 |                                 |
| (F)                            |                                 |                                 |                                 |                                 |
| Shed water collection(S)       | AS                              | BS                              | CS                              | DS(ck)                         |

2.1 Ground preparation
Measurements took place in the orchard over the period 2000 to 2002, to compare improved nutrient supply and rainwater collection with rainwater collection alone. A test plot area of 0.53 ha was used with a row spacing of 3m × 4m. This area was divided into six treatments and two controls as described in Table 1. Concentrated fertility and water collection arrangements were located in the area of most dense root distribution, at a radius of 1.0 - 1.5m from each tree. Firstly, six pits were dug, each of 30cm diameter and 40cm depth. These were filled with straw and weeds then fertilizer and water were added to each pit. Finally, each pit was filled, covered and shaped for ease of applying fertilizer and encouraging rainfall infiltration. The alternative water collection arrangements were placed within a radius of 1.0 - 1.5m from a tree and each pit was made to be a ring-like rain collection sump with a “V” shape. Then each pit was covered with mulch, and some holes were made in the sump for water to easily infiltrate. Cornstalk and some small crown flowers were used to prepare a sod mulch of about 20 cm thickness. At the same time, the butt is exposed to prevent rats, and sod is covered with some star-like earth to act as a windbreak to prevent fire. In the process of clean tillage, soil should be kept loose and weeds should be removed.
2.2 Water and nutrient determinations

A soil moisture meter was used at 10 locations to measure soil water contents at five depths. A water balance was determined for each tree. Once soil nutrients were relatively stable, 10 points were randomly chosen to collect soil samples from the 10–40 cm depth. Soil samples were evenly mixed, then a small representative sub-sample was obtained by repeated sub-division. After this, soil samples were brought for air drying in the laboratory. Finally, a spectrophotometer was used to measure organic matter, ammonium nitrogen, readily available phosphorus and potassium in the samples.

After water and nutrient measurements, 5 apple trees were selected for each treatment. Those selected were ones that had grown and yielded well. The variety used was “Changfu II” with a growth period of about 217 days. Yield per tree was determined then a production value was calculated based on the percentage and price of high quality apples. Water use efficiency was calculated from water use and yield data. A value of production benefit was calculated from the production value and water consumption.

3 Results

3.1 Water use

Table 2 shows that if all water-collecting treatment methods mentioned above are used together, straw covering can save a 6.4 % amount of gravimetric soil water in orchard surface soils, mulch covering can save 3.8 % and a weed covering can save 6.6%. Water-saving results from straw covering treatment are much better than the weed covering treatment. This is mainly because the weeds are very tender, easily rotted and quite thin after decomposition. Weed growth needs water but straw doesn’t easily rot, keeps its cover for longer and remains reasonably thick for a longer time.

### Table 2. Calculation of water consumption and Intensity of till-less and mulching rain-collecting orchard

<table>
<thead>
<tr>
<th>item</th>
<th>year</th>
<th>AF</th>
<th>AS</th>
<th>BF</th>
<th>BS</th>
<th>CS</th>
<th>CF</th>
<th>DF(ck)</th>
<th>DS(ck)</th>
</tr>
</thead>
<tbody>
<tr>
<td>water consumption (mm per year)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>water consumption intensity (m/tree x year)</td>
<td></td>
<td>2.07</td>
<td>2.17</td>
<td>2.02</td>
<td>2.10</td>
<td>2.14</td>
<td>2.24</td>
<td>2.15</td>
<td>2.38</td>
</tr>
</tbody>
</table>

### Table 3. Measurements and calculation of the content of soil nutrient of till-less and covering rain-collecting orchard

<table>
<thead>
<tr>
<th>item</th>
<th>AF</th>
<th>AS</th>
<th>BF</th>
<th>BS</th>
<th>CS</th>
<th>CF</th>
<th>DF(ck)</th>
<th>DS(ck)</th>
</tr>
</thead>
<tbody>
<tr>
<td>organic matter (g/kg)</td>
<td>11.6</td>
<td>9.5</td>
<td>16.5</td>
<td>11.6</td>
<td>15.5</td>
<td>10.4</td>
<td>11.7</td>
<td>9.0</td>
</tr>
<tr>
<td>ammonium nitrogen (mg/kg)</td>
<td>24.8</td>
<td>21.9</td>
<td>23.7</td>
<td>17.6</td>
<td>23.0</td>
<td>17.5</td>
<td>23.1</td>
<td>17.1</td>
</tr>
<tr>
<td>rapid available phosphorus (mg/kg)</td>
<td>11.3</td>
<td>8.3</td>
<td>13.4</td>
<td>8.4</td>
<td>12.3</td>
<td>8.9</td>
<td>10.6</td>
<td>8.7</td>
</tr>
<tr>
<td>rapid available potassium (mg/kg)</td>
<td>185.0</td>
<td>161.6</td>
<td>259.2</td>
<td>203.1</td>
<td>274.3</td>
<td>207.5</td>
<td>160.0</td>
<td>144.4</td>
</tr>
</tbody>
</table>

3.2 Soil nutrient levels

Table 3 shows that the concentrated nutrient and rainwater collection arrangement (F) can increase availability of soil nutrients better than the alternative rainwater collecting system (S). After the ground is covered with mulch film, the ground temperature increases and quickens the decomposition of the organic matters.

3.3 Apple yields and soil water contents

Table 4 shows that covering soil in the orchard can greatly increase the apple yield per tree. If the rootstock water-collecting treatment is used with the covering treatment together, the output has increased. The increased output brought about by mulch covering, straw covering and weed covering is 219g/kg, 205g/kg and 188g/kg, respectively, compared with the single rootstock water-collecting treatment. The combination of pit-storing fertilizer, water-collecting and mulching treatment also can increase the output of apple, being 155g/kg, 94g/kg and 114g/kg respectively.

3.4 Apple quality and production benefits

Table 4 shows that covered ground can increase the output, quality and financial benefit from apples. Compared with rootstock water-collecting treatment, the production value of apple is higher than that brought about by the hole-storing fertilizer and water treatment. For rootstock water collection, production value are 6.4 per tree. 5.4 per tree and 7.1 per tree, respectively, brought about by covering mulch, straw and weed, compared with the without cover treatment. For hole-storing fertilizer and water collection, production value are 3.8 per tree, 1.9 per tree and 1.9 per tree, respectively, brought about by covering mulch, straw and weed. When the orchard
is covered all year evaporation is decreased, providing more benefit from conserved water. For hole-storing fertilizer and water collection, benefits are ¥0.78/m³, ¥0.57/m³, and ¥0.26/m³, respectively, for improvements by mulch covering, straw covering and weed covering.

### Table 4. Output, production value and moisture production percentage of till-less covering rain-collecting orchard

<table>
<thead>
<tr>
<th>Item</th>
<th>AF</th>
<th>AS</th>
<th>BF</th>
<th>BS</th>
<th>CF</th>
<th>CS</th>
<th>DF(ck)</th>
<th>DS(ck)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output of apple (kg per one tree)</td>
<td>28.3</td>
<td>27.3</td>
<td>26.8</td>
<td>27.0</td>
<td>27.3</td>
<td>26.6</td>
<td>24.5</td>
<td>22.4</td>
</tr>
<tr>
<td>Production Value (yuan per one tree)</td>
<td>30.2</td>
<td>29.2</td>
<td>28.3</td>
<td>28.2</td>
<td>28.3</td>
<td>29.9</td>
<td>26.4</td>
<td>22.8</td>
</tr>
<tr>
<td>Percentage of moisture Production (kg/m³)</td>
<td>5.26</td>
<td>4.85</td>
<td>5.11</td>
<td>4.95</td>
<td>4.90</td>
<td>4.56</td>
<td>4.37</td>
<td>3.62</td>
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</table>

### Table 5. Moisture production benefit of till-less covering rain-collecting orchard

<table>
<thead>
<tr>
<th>Year</th>
<th>AF</th>
<th>AS</th>
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<th>CF</th>
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<tr>
<td>2000</td>
<td>3.80</td>
<td>3.70</td>
<td>3.71</td>
<td>3.16</td>
<td>3.18</td>
<td>4.25</td>
<td>3.32</td>
<td>2.37</td>
</tr>
<tr>
<td>2001</td>
<td>5.36</td>
<td>4.56</td>
<td>5.15</td>
<td>5.46</td>
<td>4.88</td>
<td>4.24</td>
<td>4.42</td>
<td>3.20</td>
</tr>
<tr>
<td>2002</td>
<td>7.39</td>
<td>7.15</td>
<td>7.06</td>
<td>6.69</td>
<td>6.94</td>
<td>6.81</td>
<td>6.47</td>
<td>5.37</td>
</tr>
<tr>
<td>Average</td>
<td>5.52</td>
<td>5.14</td>
<td>5.31</td>
<td>5.10</td>
<td>5.00</td>
<td>5.10</td>
<td>4.74</td>
<td>3.65</td>
</tr>
</tbody>
</table>

### 4 Conclusions

Both the combination of hole-storing fertilizer and water covering and the combination of rootstock collecting water and covering can improve the percentage of soil moisture and readjust the imbalance of annual precipitation distribution. Some technologies such as hole-storing fertilizer and water, rootstock-collecting water and annual mulching are applied in the orchard which located in the ravine and are applied in the orchard which located in the ravine and gully areas in the highland so as to fully utilize natural precipitation to meet the need of apple growth and bearing fruit.

The adequate fertilization in the hole and the rain collection sump, and the collected runoff can make water and fertilizer combine in the time and space; and also the annual covering technology can reduce the soil erosion, prevent the loss of water and fertilizer, improve the utilization ratio of fertilizer and increase the content of soil nutrients. These are effective measures to grow apple with high quality and benefit. The combination of the hole-storing water and fertilizer and the covering technology, and the combination of rootstock water collection and covering technology have improve the output, quality and benefit of apple, and increased the percentage and production benefit of moisture. In addition, after mulching technology is applied in the orchard, zero tillage has not destroyed the structure of soil and decreased the density and speed of weed growth. Therefore, the intensity of labor and the investment have decreased.

The hole-storing water and fertilizer and the covering treatment can make the local resources of straw be fully used And growing the green manure in the unoccupied place which is between the groves and weeds have changed the traditional system of clean tillage. Besides these, the hole-storing water and fertilizer is carried out in the orchard, and the hole should be dug once every year because the butt will extend outwards to the rain-collecting sump every year and the butt becomes big with the age of tree growing old.

### References


Spring drought protection measures in western Heilongjiang Province

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Abstract
Measures for avoiding spring drought stress are examined. A combination of deep tillage and application of river silt was shown to improve water retention capabilities. Autumn cultivation should be avoided where possible. So, the most suitable range of soil water for spring cultivation is 16%~20%, if irrigation water is available to help create this. For minimum soil water loss, ploughing, harrowing and ridging should be completed quickly. Other key measures include increasing the proportion of drought-resistant varieties being and enlarging the area of protected land.

Key words: Drought affects; soil water; measures of drought-resistance.

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1 Introduction
1.1 Drought characteristics
Drought is a serious natural problem in spring. Over a 30-year period from 1949 to 1979, there were 22 incidences of drought in the western region, representing 73.3% of the time span. High yields could not be achieved and keeping a full stand of seedlings after spring seeding was especially difficult. So identifying effective measures to counter spring drought are important, if it is reasonable to expect that farming should continue in the area. Annual average rainfall is 394 mm, falling predominantly from July to September. At that time rainfall can meet the needs of crop growth with even some surplus rainfall. Sometimes there is a problem of draining flooded fields and preserving this soil moisture.

Earlier research suggests that there are two peaks of critical soil water supply for spring crops. One is from the last ten-day period of March to the first ten-day period of April, while the other is from the last ten-day period of April to the first ten-day period of May. If successful sowing is completed before the middle ten-day period of May, then keeping a full stand of seedlings can be ensured. Good seed-bed preparation means a stable layer of soil water content in the range 15%~20%. Such a soil water content can meet germination needs of seeds sown in the layer.

1.2 Improving soil water storage
Means of conserving excess summer rain are necessary to help crop establishment in the following spring, since groundwater is unavailable. Measures to improve soil conditions include deep tillage, deep scarification and increasing soil organic matter content. Deep tillage and scarification improve soil structure and reduce surface flow, but don’t improve water storage. Such ability depends on increasing soil organic matter. Spreading organic fertilizer, planting green manure and incorporating straw into soil all do this. For every 0.1% fall in organic matter, over 250kg of organic fertilizer must be applied annually to restore fertility.

1.3 Reducing evaporation loss
Covering with plastic film prevents evaporation loss and can conserve soil water. In 1985 and 1986, when the drought was very serious, planting maize covered by plastic film was investigated in Yi’an county of Heilongjiang Province. The average yield was 700 kg/ha and only slightly reduced from normal conditions. Without the treatment, traditional planting measures only yielded 200~430 kg/ha. Deciding on whether to plough soils in autumn or in spring might also be expected to have an influence on soil water conservation.

2 Materials and methods
Three soil treatments were arranged to investigate potential improvements from deep tillage and applying river silt, applying river silt and no deep tillage or deep tillage and not applying river silt. Field soil water contents were determined for these and a range of other soil husbandry practices, to identify those that conserved the greatest amount of soil water for spring growth. Measurements were made in the top 20 cm soil layer, both in autumn and spring.

3 Results
Table 1 shows that field soil water contents of the deep tillage plots without the river silt treatment were similar to the control plots. Combining deep tillage with the river silt
treatment increased the moisture contents by 4%~5% more than the control plot. Only field soil water contents within 0~10cm layer were increased, after applying river silt with no deep tillage. So when deep tillage is combined with spreading river silt and related organic matter, then this improves the soil water holding capacity. In the 0~20cm layer, sand content reduced from 74% to 50% with silt and clay increasing from 26% to 50%, while soil organic matter increased 68%, and water holding capacity improved by 63%.

Table 1. Each method of effecting the soil moisture content

<table>
<thead>
<tr>
<th>Soil horizon</th>
<th>Method of improving soil</th>
<th>Check plot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M₁</td>
<td>M₂</td>
</tr>
<tr>
<td>0~10cm</td>
<td>26.9</td>
<td>35.1</td>
</tr>
<tr>
<td>10~20cm</td>
<td>24.9</td>
<td>22.8</td>
</tr>
<tr>
<td>20~30cm</td>
<td>25.9</td>
<td>20.2</td>
</tr>
<tr>
<td>average</td>
<td>25.9</td>
<td>26.0</td>
</tr>
</tbody>
</table>
M₁: Deep tillage and applying river silt; M₂: Applying river silt and no deep tillage; M₃: Deep tillage and not applying river silt.

Table 2. The status of soil moisture in every layer

<table>
<thead>
<tr>
<th>Layers</th>
<th>Content of soil moisture with different treat (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0~5cm</td>
<td>Former ridge (millet stubble)</td>
</tr>
<tr>
<td>5~10cm</td>
<td>6.47</td>
</tr>
<tr>
<td>10~15cm</td>
<td>16.56</td>
</tr>
<tr>
<td>15~20cm</td>
<td>16.09</td>
</tr>
<tr>
<td>20~30cm</td>
<td>18.19</td>
</tr>
<tr>
<td></td>
<td>18.80</td>
</tr>
</tbody>
</table>

Table 3. The content of soil moisture in ridged and stubbed in fall

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0~5cm</td>
<td>T₁</td>
<td>10.0</td>
<td>13.9</td>
<td>7.9</td>
<td>13.9</td>
<td>14.8</td>
<td>9.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5~10cm</td>
<td>CK₁</td>
<td>15.2</td>
<td>14.6</td>
<td>14.3</td>
<td>16.9</td>
<td>16.6</td>
<td>5.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10~15cm</td>
<td>T₂</td>
<td>16.6</td>
<td>17.7</td>
<td>5.6</td>
<td>19.8</td>
<td>19.8</td>
<td>19.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15~20cm</td>
<td>CK₂</td>
<td>16.6</td>
<td>17.7</td>
<td>5.6</td>
<td>19.8</td>
<td>19.8</td>
<td>19.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
T₁: Rridged in fall; T₂: Stubbed field; CK₁: ridge of check group; CK₂: Furrow of check group.

Tables 2 and 3 show that ability to preserve soil water in old ridges was better than autumn cultivation. If autumn cultivation is essential, then this must also include harrowing and rolling to compact soils again. Ploughing is best done under soil water conditions that avoid producing large clods. Experiments showed that a friable tilth was produced when working at 19.2% water content. When soil water contents were below 12.5%, then there were some irregular clods after cultivation. Above 23% water content conditions became too sticky. So, the most suitable range of soil water content is 16%~20%. If water is available then it is the best to irrigate once in the fall, after ploughing, harrowing and ridging. For minimum soil water loss, ploughing, harrowing and ridging should be completed quickly.
Section III

Irrigation Practice and Water Management
Water saving small-holder irrigation: Experience from Africa

Nico van Leeuwen

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Abstract

Necessary condition are discussed for successful use of drip irrigation by small-holder farmers. Information is based on experience of testing equipment at the Interstate School for high level Technicians in Hydraulics and Rural Engineering near Ouagadougou, in Burkina Faso. Drip systems should be affordable to be adopted by small holder farmers in rural areas. They should be low-cost relative to farm income, easy to install and operate by farmers without particular technical training, cost effective with investment recouped in one season and have low operation and maintenance costs. Companies are proposing systems covering 500-2000 m$^2$ that meet these needs, except that water supply arrangements may be oversimplified. Inclusion of treadle and kerosene pumps has been important in this respect. Markets for vegetable crops should be well established and within reasonable distance from cultivated area. Farmers should receive additional agronomic assistance for long periods. Clusters of smallholder farmers practising irrigation will lead to savings on part of the infrastructure and in particular on the cost of pumping. Such clusters could employ a “water man” who takes care of the water provision. To make the technology available to poor farmers, subsidies should be provided and a small-scale credit system should be put into place.

Key words: Necessary conditions, drip irrigation, small-holder farmers, clusters, cost of pumping.

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1 Water, food security and poverty alleviation

In the last 40 years the world population has doubled while during the same period, the number of undernourished people has decreased both in numbers and as percentages. Since 1992, the number of hungry people has decreased by some 2.5 million per year. This would show that food production has outpaced population growth and that malnutrition and hunger are in slow but constant decline. This is true at the global level; however, this optimistic assessment is the result of significant progress in a small number of countries, mainly in Asia, and in particular the very important reduction of undernourished people in China. In most developing countries the percentage of hungry people has decreased, however, the number still has increased because of the population growth. Progress in reducing the number of hungry people is much too low to reach the goal established by the World Food Summit in 1996 to halve the number of hungry people by 2015. Increased productivity of land and water is a primary element of strategies to eradicate poverty. Increased agricultural production will increase employment in the agricultural sector. It will promote the development of agro-industries and related trade activities. Demand for consumption goods and services will also increase.

Participants in the E- Conference on Irrigation in Sub-Saharan Africa organised by the Word Bank from 13 January to 21 February 2003 acknowledged the important role of smallholder irrigation. The report of this Conference (World Bank 2003) states that the technologies for small-scale irrigation have passed the pilot stage and have obtained considerable success in many countries. Smallholder irrigation is important in particular for women farmers: “In many African countries women are the ones who take care of the family garden and small scale irrigation can provide the means for food production in the dry season. Her family already lives where the need for food is located. She does not need the government to build new roads to transport her vegetables to a distant market. She can be self-sufficient and not have to depend on relief food to take care of her family. Often she can grow a few extra vegetables and sell them to her neighbours. Small scale irrigation technologies are suited to addressing the needs of these millions of women and their families.” The report concluded that more attention should be given to smallholder irrigation and that ways and means should be identified to increase investment.

2 Low-cost drip irrigation systems
Technologies have been developed to conduct water through pipes to the fields, to apply the water in small quantities, directly to the plant root area and to avoid wetting of large soil areas at the surface. A number of different localised irrigation systems have been developed with the introduction of plastics in irrigation equipment some 50 years ago. In addition to improved water efficiency, drip irrigation systems require less labour, allow efficient application of fertilisers and result in fewer occurrences of diseases and pests with higher quality products. The adoption of small-scale low-cost drip irrigation technologies by small holder farmers could be one of the solutions to increase food production, increase farmer’s income and improve food security.

To be adopted by small holder farmers in rural areas, drip systems should be affordable. This means that they should be low-cost relative to farm income with an investment cost as low as possible, easy to install and to operate by farmers without particular technical training, cost effective with investment recouped in one season and have low operation and maintenance costs. Different organisations and companies\(^1\) are proposing systems that correspond more or less to the above requirements. These systems have a number of features in common (Van Leeuwen, 2001).

**Water supply** Most of the small-scale systems are supplied with water from a bucket, drum or water container that is installed in the field close to the cropped area. Depending on the dripper laterals, these reservoirs are installed on a stand or platform between 1 and 2.5 meters above field level. Dripper laterals can be connected directly to the water reservoir itself or to a main distribution pipe. In some cases it is assumed that the irrigation water is supplied by a pressurised system.

**Water quality** All systems have some kind of filtering of the irrigation water in order to avoid the clogging of the drippers by impurities. Such a filter is sometimes limited to a piece of cloth that filters the water where it enters the reservoir. Other systems are provided with a disk or screen filter. The need for a more secure filtering with a sand filter if water is very dirty is mentioned by a number of suppliers.

**Water distribution** Several systems are proposed with laterals that have drippers built-in at specific distances (such as 30, 45, 75 cm). Others have low-density polyethylene laterals on which drippers can be fixed. Several lines of plants can be irrigated if micro tubes are fixed to one lateral. Sometimes the drippers are reduced to a simple hole in the lateral.

**Cost** Investment cost for most of the systems is relatively low. The cost of the kits that are proposed varies between US$ 5 and US$ 100 per unit (depending on the area covered). These costs exclude any equipment for the mobilisation of water (boreholes, wells, pumps, canals, etc.) as well as the cost of the reservoir (buckets, drums). The information provided by the suppliers varies from one system to the other and makes it difficult to proceed with a comparison. The general impression that is given in all the documentation is that these drip irrigation kits are cheap, do not require much water and are not labour demanding. The reality is different. While there is no doubt about the merits of low-cost small-scale drip kits, there is in most of the cases an over-simplification in the presentation. There are serious risks that users are confronted with unexpected problems and, not finding easy solutions, they may abandon the drip system and return to their traditional watering methods with cans. Some of the critical issues are the following:

**Potential irrigated areas** The area covered by the proposed drip irrigation kits varies between 25 and 500 m\(^2\). This area is generally based on the length of the dripper laterals and the distance between the lines. Consequently the same kit can cover an area of 500 m\(^2\) and 2000 m\(^2\) when the distances between the drip lines are increased from 0.75m to 3.00 m. A comparison between the different systems should consequently not be based on the area covered but on the length of drip line provided in the kit. The distance between the drip lines should depend mainly on the optimal distance between the rows of plants, which varies from one crop to another. The area actually covered by the system will influence strongly the amount of water that is needed.

**Investment cost** The different kits are offered for prices that vary from US$ 5 to US$ 100. Independently of the actual areas covered by these systems as discussed above, the cost per hectare would amount to some US$ 2,000. Not included are the costs of the water point, the pump, the sand-filter (if required) and the connecting pipes. Taking into account all these additional elements the total cost of a complete set of equipment for small-scale drip irrigation may vary between US$ 5,000 and US$ 7,500 per ha (Keita, 2001).

**Crop water requirements** Some of the kits are accompanied by indications that with two buckets or two drums of water a day a farmer can irrigate a given area. If those indications are followed, the actual amount of water supplied to the crops varies between 1.6 and 9 mm/day. Several kits give indications that in warm climates more water could

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\(^1\) Chapin Watermatics Inc., International Development Enterprises (IDE), Netafim, Aquatec.
be needed. The actual water requirements depend also on the crop that is grown as well as on the development stage of that crop. Further, the effect of plant population or plant density on the crop water requirements is similar to that of the percentage of ground cover (Doorenbos, 1992). When the topsoil is kept relatively dry, evaporation from the soil surface is sharply reduced and ET crop will be less for low population crops than for high population crops. During the early stage of a crop a high population planting would normally require somewhat more water than a low density planting due to quicker development of full ground cover. In irrigated agriculture plant population has been considered of little importance in terms of total water needs. In general water requirements will depend on the total area covered. A more practical problem is that drip irrigation does not allow a visual control of the amount of water that is applied to each plant. Consequently farmers will need assistance to determine the quantity of irrigation water required and how to make sure that this quantity is applied.

Water supply The documentation on drip irrigation kits gives the impression that the organisation of the water supply is not really a problem. By providing just 2 buckets of water (of 20 litres each) in the morning and in the afternoon the water requirements of a plot of 40 m² would be covered. In fact this would just amount to 2 mm/day and in certain circumstances the plants may require 8 mm/day corresponding to eight trips from the water sources with 2 buckets of 20 litres each. When it gets to filling a 200 litres drum several times a day, there is clearly need to pump water into the system. In most cases individual farmers would be able to use a treadle pump however the cost of the pump, the dug-well and connecting pipes should be added to the investment cost the same as the cost of the buckets or drums. The labour cost for the pumping of the water should be added to the operations cost.

Filters. For some of the bucket kits, the filtering of the water is done by a piece of cloth. Most kits have filters, some very simple screen filters others with more sophisticated screen filters without however mentioning the actual performance of these filters. Sand or gravel filters are mentioned as they could be used to treat more heavily charged water. The documentation does not mention any specific filtering requirements for the different types of drip lines. It only mentions that some of the systems are easy to clean. The information received, after specific request, from one of the suppliers of drip lines, has given clear indications with regard to the actual filtering requirements.

These filtering requirements (from 125 to 80 microns) also depend on the working pressure, and consequently the actual discharge, of the drippers: with a higher discharge, the level of filtration can be reduced.

Fertigation The application, through the drip system, of nutrients dissolved in water is called fertigation. Since the fertilizer reaches directly the root zone, fertigation is the most efficient way for the application of fertilizers. The increased production will allow a better valorisation of the investment made by the farmer in the drip irrigation equipment. Only one supplier mentions the possibility of fertigation in its documentation. Farmers will need advice on the advantages of fertigation and should be trained in the selection of the liquid fertilizer and the procedures for its application through the drip system.

Flexibility Most of the kits are supposed to be used on flat land and rectangular fields. Drip tapes have fixed distances between the drippers that cannot change. These systems cannot accommodate fields on slopes or different crops, which may present problems when farmers need to irrigate different crops.

In order to make a successful use of the drip irrigation system, farmers will need advice and training. Part of the training and advice could possibly be included in the package that the farmer purchases from the supplier. This could also include trouble shooting during the first season. Other services dealing with the selection of crop varieties, disease and pest control, marketing, etc. should be provided by the specialised government services.

Most of the above mentioned issues can be dealt with without too much problems. The quality of the water and the selection of the type of drip lines however will require special attention.

3 Applied Technology Research on Small holder Irrigation

3.1 Supply, Transport and Distribution of Irrigation Water

A number of simple irrigation technologies have been tested at the Ecole Inter-Etats des Techniciens Supérieurs de l’Hydraulique et de l’Equipement Rural (ETSher – Interstate School for high level Technicians in Hydraulics and Rural Engineering) near Ouagadougou (Burkina Faso) (Keita, 2001). This had Japanese funding and direction from FAO. Both surface water from a nearby lake and groundwater from dug wells were used.

On most of the small garden plots in sub-Saharan Africa, water is carried by hand from the nearby
lake or is lifted from the dug-well. This practice is very labour intensive and the area that can be irrigated is limited by the available manpower. Treadle pumps make a better use of manpower and allow irrigating a larger area up to 0.25 ha. These pumps are at present manufactured in most countries and repair and maintenance is available in the rural areas. Several types have been tested by the project and the “suction/pressure” type is most suitable as it allows delivering water under pressure to a higher situated storage tank or directly through a pipe or hose to the irrigated parcel. For the irrigation of larger areas the project has tested kerosene pumps as this type of fuel is cheaper and more easily available in rural areas.

Water is scarce in arid and semi-arid areas and its supply is costly. Consequently, it is important that little water is lost during transport and its distribution to the irrigated parcel. Low-cost PVC pipes are available with local suppliers in different sizes. As pressure will remain low, the cheaper sanitary discharge type PVC tubes are being used. An additional advantage of a low pressure closed system is that it allows the distribution of water over an uneven area and avoids the need for levelling that is required for most surface irrigation systems.

3.2 Irrigation Systems

Once the water arrives at the plot, it should be distributed to the plants in the most efficient way. All the systems described hereafter use PVC sanitary type tubes and some flexible hoses. The use of special parts such as elbows, T-parts, stops, etc is limited as much as possible and most of these are manufactured locally which reduces the total cost.

Drip irrigation is indeed the most efficient irrigation system as it brings the irrigation water in small quantities directly to the root zone of the plants. Drip laterals with built-in drippers at regular distances have become relatively cheap and are available on the market from several manufacturers. They are designed to function under medium pressure (0.5 – 1.0 bar) but are also performing relatively well under lower pressure (0.1 – 0.3 bar). Their main problem in field conditions is clogging of the drippers or emitters when water contains silt or clay. Simple filters are recommended but these are not always sufficient to clean the water from the very small particles.

For such conditions the project has developed a drip system with a buried main, equipped with short ends of flexible connecting hoses at regular distances (distance of plant rows) and situated in the middle of the parcel. These flexible tube ends can be oriented to either side of the main. When not in use, the end of the flexible hose is closed by folding. A mobile drip line can be connected to these flexible hoses. It is made from 18 mm PVC in which 3 mm drip holes are made every 30 cm. To break the water jet coming from these holes, they are covered with a 10 cm long piece of the same tube that has been cut over length and is kept in place with a string made from used bicycle inner tube. Drip holes can easily be cleaned. At regular intervals, this mobile drip line is disconnected from the flexible tube and moved to the next row.

![Pump](image1.png)  ![Local drip](image2.png)

(a) Pump  (b) Local drip

Furrow irrigation from flexible tubes is most appropriate when a motor pump is available. Also in this system, the main tube is buried in the middle of the plot and the flexible tubes deliver the water directly to the furrows on both sides. Depending on the discharge of the pump, several furrows are irrigated at the same time.
Bubblers have been tested in particular for tree crops. Each tree is provided with a bubbler (vertical end of 20 mm PVC pipe) that provides water to a small basin at the foot of the tree. Several bubblers are operating at the same time. Water can be pumped into the system directly with a treadle pump, but in view of the relatively high discharge of the bubblers, it may be advisable to pump the water into a reservoir and only irrigate when sufficient storage has been built-up.

The Californian irrigation system transports the water to the top-end of a tertiary canal where a 50 mm PVC tube with elbow stands up. From the tertiary canal, the water is distributed to short furrows or small basins depending on the crop that is grown. This system requires a motor pump in view of the relatively large discharge of the outlets. In order to reduce the losses, the tertiary canal can be replaced by a 50 mm PVC pipe equipped with 20 mm standpipes at regular distances. As the discharge is lower, this last system can be served with a treadle pump.

Detailed description and cost estimates of the six different irrigation systems that were developed and tested by the above-mentioned FAO project at its site at Ouagadougou, Burkina Faso, are presented in the table below.

3.3 Conditions for success with small-scale low-cost technologies for smallholder farmers.

To invest in water saving irrigation technologies, the water users should have the strong feeling and experience that water is scarce and limited in amount (ITC 2003). A water source should be available close to the production area. Farmers should be used to cultivating those types of vegetable crops that can be irrigated with drip irrigation. Growing vegetable crops should be the most appropriate crop for those areas. Markets should be well established and within reasonable distance from the cultivated area.

In addition to technical assistance for the operation and maintenance of the drip system, farmers should receive additional agronomic assistance for long periods. If no particular advice is provided, water supply to the crops will not follow the actual requirements and water consumption will remain high.

The establishment of clusters of smallholder farmers practising irrigation will lead to savings on part of the infrastructure and in particular on the cost of pumping. Such clusters could employ a “water man” who takes care of the water provision. One water-man can provide services for several clusters. Alternative labour possibilities should exist through which farmers can earn the cash needed for the purchase of the equipment. To make the technology available to poor farmers, subsidies should be provided and a small-scale credit system should be put into place.

4 Conclusions

Water alone is not sufficient to guarantee a good harvest and other inputs such as seed, fertiliser and pesticides are also needed. While large-scale farmers may have some financial capacities to absorb crop failures, smallholder farmers cannot allow themselves to run such risks. For this reason, smallholder farmers are always very reluctant to invest into agriculture. This is especially so when the supply of water, the key element for agricultural production, is not under control. Smallholder farmers are also very reluctant to
invest in improved irrigation methods unless the major benefits in terms of increased production and better crop quality are evident. Other preconditions are easy access to markets and credit facilities. Technical support is needed for a relatively long period to make sure that farmers are fully mastering the new technology and that no specific technical problems will force them to discard the equipment and loose the investment.

Table 1. Tested water transport and distribution systems

<table>
<thead>
<tr>
<th>Nomination</th>
<th>Description</th>
<th>Cost of system US$/ha</th>
<th>Usual additional equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buried main with fixed drip lines</td>
<td>The buried main pipe conducts the water to the top end of the field where outlets are connected every meter. The drip lines are connected to these outlets.</td>
<td>4,180&lt;sup&gt;2&lt;/sup&gt;</td>
<td>Treadle, pumps (5), tanks(5), sand filters(5), dug well(s)</td>
</tr>
<tr>
<td>Buried main with mobile drip line</td>
<td>The buried main pipe conducts the water to the top end of the field where flexible outlets are connected every meter. A mobile, locally constructed, drip line is moved from one outlet to the next outlet at regular times when the required water amount has been delivered to a row of plants</td>
<td>1,523</td>
<td>Treadle pumps(5), dug well(s)</td>
</tr>
<tr>
<td>Buried main with flexible hose outlets</td>
<td>The buried main pipe conducts the water to the top end of the field where water is delivered to furrows by 1 m long ends of flexible hose, connected every 1 m</td>
<td>1,060</td>
<td>Motor pump, dug well(s)</td>
</tr>
<tr>
<td>Buried main and laterals with bubblers</td>
<td>The buried main pipe delivers water to a number of buried laterals. These laterals are equipped with vertical outlets (bubblers).</td>
<td>4,435&lt;sup&gt;3&lt;/sup&gt;</td>
<td>Treadle pump(s), dug well, concrete tank</td>
</tr>
<tr>
<td>Buried main with Californian outlets</td>
<td>The buried main pipe conducts the water to the top end of the field where 50 mm vertical outlets deliver the water to an unlined canal. Through the unlined canal the water is delivered to the small basins mainly for cultivation of vegetables</td>
<td>1,228</td>
<td>Motor pump, dug well(s)</td>
</tr>
<tr>
<td>Buried main and laterals with Californian outlets</td>
<td>The buried main pipe delivers water to a number of buried laterals. These laterals are equipped with vertical Californian outlets that deliver water to small (6 m&lt;sup&gt;3&lt;/sup&gt;) growing beds.</td>
<td>8.130</td>
<td>Treadle pump(s), dug well</td>
</tr>
</tbody>
</table>
| Other items that should be added as and when required: Petrol pump | Kerosene pump $ 650   Treadle pump $ 100   Dug well (10 m deep) $ 500   Concrete 4.5 m<sup>3</sup> tank $ 125<br><br>Sand filter $ 260 2000l tank $ 340 | $500<br><br>Cost includes 5 plastic 2,000 litre reservoirs @ $ 340 = $1,700<br><br>Cost includes 4 concrete tanks of 4.5 m<sup>3</sup> each @$125 = $500
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Modeling the sink term under variable water stress

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Abstract

The influence of water shortage on the water extraction pattern has been quantified for periods of water stress. A macroscopic water extraction model combined with the Richards’ equation was inserted in the numerical simulation model HYSWASOR, to test four different water stress functions. Input parameters were obtained from the literature and derived from extensive measurements of alfalfa, under well-controlled conditions in a greenhouse. Results indicated that a linear reduction function could not fit the experimental data range satisfactorily. Most of the existing nonlinear reduction functions could only fit a part of the data range, while best agreement was obtained with a nonlinear two-threshold reduction function. Parameter values obtained by calibration differed only slightly from those of the experiments. The heterogeneity of matric potential over the root zone did not play a significant role in water uptake. Roots appeared to take up water from relatively wetter parts of the root zone to compensate for water deficit in drier parts. The main reason for small discrepancies between measured and simulated water contents appeared to be water uptake during darkness over the stress period.

Key words: root water uptake, sink term, water stress, arid, semi-arid

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1 Introduction

Water scarcity is the prime limitation for crop production in arid and semi-arid regions. Quantitative description of this process is central for many applications as well as modeling and simulation purposes. Two main approaches exist to quantify root water uptake. The most important limitation of the so-called microscopic approach in terms of application is the unavailability of the required input parameter values, particularly those at the root surface (Homaee et al., 2002; Gardner, 1991; Feddes, 1981; Molz, 1981; Feddes et al. 1978). The second, so-called macroscopic approach, is an empirical function that describes plant water uptake based on the observed response to soil water pressure head (Homaee et al., 2002; Dickson et al., 1993; Van Genuchten, 1987; Van Genuchten and Hoffman, 1984; Feddes et al. 1978). The most common formulation of this approach is based on the work of Feddes et al. (1978). The advantage of the macroscopic approach is that it does not require complete insight into the physical process of root water uptake and, therefore, eliminates the need for soil and plant parameters that are difficult to obtain. Such an empirical approach still needs to be calibrated, however, for different plants and different climate conditions (Homaee and Feddes, 2001, 2002). This study aimed to verify which macroscopic water stress function can provide the best correlation with the experimental data, and to investigate the impact of variable water stress levels on the root water uptake pattern.

Water flow in unsaturated soils is described with the Richards’ equation (Richards, 1931):

\[
\frac{\partial^2 h}{\partial t^2} - \frac{1}{K(h)} \frac{\partial}{\partial z} \left( K(h) \frac{\partial h}{\partial z} \right) = \frac{\partial S(h)}{\partial z} \tag{1}
\]

where \( \theta \) is volumetric water content (L\(^3\)L\(^{-3}\)), \( t \) is time (T), \( h \) is soil water pressure head (L), \( z \) is gravitational head, as well as the vertical coordinate (L) taken positive upwards, \( K \) is soil hydraulic conductivity (LT\(^{-1}\)), and \( S \) is soil water extraction rate by plant roots (L\(^3\)LT\(^{-1}\)).

The unsaturated soil hydraulic functions in Equation 1 are the soil water retention curve \( \theta(h) \) and the hydraulic conductivity function \( K(h) \). The analytical function of Van Genuchten (1980) for \( \theta(h) \) can be written as:

\[
\theta_r \left( \theta \right) = \left( \frac{\theta - \theta_s}{\theta_r - \theta_s} \right)^{n} \left( \frac{\theta_r - \theta_s}{\theta - \theta_s} \right)^{m} \tag{2}
\]

where \( \theta_r \) and \( \theta_s \) are residual and saturated water contents, respectively; and \( n \), \( (L^3) \), \( m \) (-), and \( n \) (-) are shape factors. The latter can be taken equal to 1-\( 1/n \).

The soil hydraulic conductivity function can be described by (Mualem, 1976; Van Genuchten, 1980):

\[
K(h) = K_0 S_e^{\alpha} \left[ 1 + \left( \frac{S_e}{1 + S_e^{1/m}} \right)^m \right]^2 \tag{3}
\]
where $K_s$ is the saturated hydraulic conductivity (LT$^{-1}$) and $l$ (-) is a shape factor. Feddes et al. (1978) introduced a macroscopic sink term depending on soil water pressure head $h$ only as:

$$ S = \frac{h}{h_3} S_{\text{max}} $$

in which $S_{\text{max}}$ is the maximum water uptake rate and $? (h)$ is a dimensionless function of pressure head. The pressure head-dependent reduction functions used in the simulations are those proposed by Feddes et al. (1978), van Genuchten (1987), Dirksen et al. (1993), and Homaee (1999). The reduction term of Feddes et al. (1978) reads:

$$ ? (h) = \frac{h}{h_3} \frac{h_4}{h_3} $$

in which $h$ is soil water pressure head, $h_3$ is the soil water pressure head threshold value and $h_4$ is the soil water pressure head at wilting. Alternatively, van Genuchten (1987) proposed:

$$ ? (h) = \frac{1}{? ! + \frac{2}{? h} \frac{?^p}{? h_4}, \frac{?}{? h} \frac{?^p}{? h_4}, \frac{?}{? h} \frac{?^p}{? h_4}} $$

in which $h_{30}$ is the soil water pressure head at which $? (h)$ is reduced by 0.50. Dirksen et al. (1988, 1993) modified Equation 6 by assuming that root water uptake is not reduced above a threshold value of soil water pressure head $h^*$, and introduced:

$$ ? (h) = \frac{? ! + \frac{2}{? h} \frac{?^p}{? h^*}, \frac{?}{? h} \frac{?^p}{? h^*}, \frac{?}{? h} \frac{?^p}{? h^*}, \frac{?}{? h} \frac{?^p}{? h^*}} \frac{1}{? h^* - h \frac{?}{? h} \frac{?^p}{? h^*}, \frac{?}{? h} \frac{?^p}{? h^*}, \frac{?}{? h} \frac{?^p}{? h^*}, \frac{?}{? h} \frac{?^p}{? h^*}} $$

Homaee (1999) introduced a second threshold value in Equation 7, replaced $h_{30}$ with $h_{\text{max}}$, and proposed:

$$ ? (h) = \frac{1}{? ! + \frac{2}{? h} \frac{?^p}{? h^*}, \frac{?}{? h} \frac{?^p}{? h^*}, \frac{?}{? h} \frac{?^p}{? h^*}, \frac{?}{? h} \frac{?^p}{? h^*}} $$

in which $h_{\text{max}}$ (the second threshold value) is the soil water pressure head beyond which changes of $h$ no longer influence the relative transpiration significantly, and $?_0$ is the relative transpiration at $h_{\text{max}}$. Similar to Van Genuchten (1987) he further assumed that the dimensionless exponent $p$ is crop, soil and climate-specific and proposed:

$$ p = \frac{h_{\text{max}}}{h_{\text{max}} - h} $$

2 Materials and methods

Growing of alfalfa (Medicago Sativa L.) was carried out under controlled environmental conditions in a highly instrumented greenhouse. Alfalfa was seeded in packed cylindrical soil columns with a height of 65 cm and a diameter of 21 cm. Measurements started after healthy plants had developed. Assuming no water uptake during dark periods, all irrigation water was applied to the columns by flood irrigation immediately before turning off the lights. This aimed to allow applied water to distribute over the root zone at times when the plants did not transpire water. With a few exceptions, all measurements started after switching on the lights. The light period normally was 15 hours per day until 9.00 pm. Fully automated TDR equipment was used to measure water content across the root zone. All sensors were installed horizontally into the soil columns in one row at 5 cm intervals in the top 30 cm and every 10 cm below that. Soil water pressure heads $h$ were obtained by converting $? to h based on the soil water retention characteristics. The soil hydraulic functions were obtained from a laboratory experiment with the evaporation method of Wind (1966). The nonlinear least-squares optimization program RETC (Van Genuchten et al., 1991) was used to obtain the values for the parameters in Equations 2 and 3.

Two water stress treatments ($W_1$ and $W_2$) and a control treatment ($R$) were established in the greenhouse. The target amount of applied water for the first level of water stress $W_1$ was 70% of the no-stress treatment $R$, while the second level $W_2$ received about 50% of the irrigation water of $R$. The irrigation intervals were 3-4 days. Tap water was applied to the soil columns by flood irrigation. Inert granules covered the top of each column to minimize evaporation from the soil surface.

The $W_1$ treatment was used for calibration. Simulations with different root activity distributions indicated a reasonable influence on simulated water contents, particularly at higher water contents. Closest agreement between simulated and experimental water content distributions was obtained with an exponential root activity distribution. Accordingly, in all the simulations the same distribution was specified.

3 Results and discussion

Figure 1a shows samples of experimental and simulated water content distributions obtained with the reduction term given by Equation 8 for one irrigation interval of the $W_1$ treatment. The simulated trend of water content changes was reasonable, but there were some discrepancies between this and the actual values. Irrespective of what reduction function was used, these discrepancies were especially high when evaporative demand was high. In most cases, the disagreement started during the second night after irrigation and increased with time. These observations suggested closer examination of water
content distributions during the dark period. The column weight remained exactly the same during the dark period, indicating that no water was transpired. However, water content decreased in the top 25 cm of the soil columns, but not in the deeper parts. This always happened between 21.00 to 4.00 h; thereafter, water contents remained unchanged until the lights were turned on at 6.00 am. Thus, any uptake due to low natural light intensities between 4.00 and 6.00h was unlikely. Before 4.00h, the plants must have taken up water from the upper part of the soil column and stored it in their tissues. This is supported by the recovery of the leaf water potential. Typical changes in soil water content over the root zone during the dark period of the stressed treatments are given in Figure 1b.

![Figure 1](image)

Figure 1. (a): Experimental (E) and simulated (S) water content distribution over the root zone; (b): experimental water content changes during the dark period: t1, immediately after darkness; t2, just before turning on the lights; t3, after 4h of light.

Simulation of actual transpiration with Equation 5 for different \( h_3 \) values indicated that this model is more sensitive to \( h_3 \) than to \( h_4 \). For example, simulated actual total transpiration for one growth period changed about 12 mm between \( h_3 = -600 \) to -400 cm, while decreasing \( h_3 \) from -3500 to -5500 changed the transpiration about 5 mm. The closest agreement between simulated actual transpiration and experimental data of \( W_i \) was obtained with \( h_3 = -800 \) cm and \( h_4 = -3500 \) cm. These values were used in all following simulations of \( W_1 \) and \( W_2 \) with the reduction function of Equation 5. The parameter values used in the simulations are given in Table 2.

Sensitivity analysis indicated that simulated actual transpiration with Equation 6 is sensitive to \( h_{50} \) as well as to \( p \), as expected for a nonlinear function. By changing \( p \) from 3 (proposed by Van Genuchten, 1987) to 1.15 (found in the current experiment) total actual transpiration changed only about 3 mm. The model is more sensitive to \( h_{50} \) than \( p \), as total transpiration changed about 8 mm when \( h_{50} \) decreased from -2000 to -1800 cm. The best result was obtained with \( p = 1.15 \) and \( h_{50} = -2000 \) cm (Table 2), but these parameter values resulted in an overestimation of transpiration. The closest agreement between actual transpiration and experimental data was obtained for \( h_{50} = -1800 \) cm. These values were used in the following simulations of \( W_1 \) and \( W_2 \) with Equation 6 (Table 2).

Equation 7 was sensitive to \( h_{50} \) as well as to \( p \) and \( h^* \), but not as much as Equation 6. The shape of Equation 7 is dominated by three parameters \((p, h^*, h_{50})\). The parameter values were first taken from the best experimental fit; namely \( h^* = -1000 \) cm, \( h_{50} = -2000 \) cm and \( p = 1.15 \). However, actual total transpiration simulated with these values was slightly overestimated. The closest agreement between simulated actual total transpiration and experimental data of \( W_i \) was obtained by changing the parameter values to \( h^* = -800 \) cm, \( h_{50} = -1600 \) cm and \( p = 1.25 \). In all following simulation of \( W_1 \) and \( W_2 \) with Equation 7, these values were used (Table 2).

Sensitivity analysis indicated that the reduction term of Equation 8 is neither sensitive to \( p \) nor to \( h_{\text{max}} \), and only slightly sensitive to \( h^* \) and \( ?_0 \). Total actual transpiration changed about 3 mm when \( h^* \) was changed from -800 to -600 cm. The same difference of 3 mm was obtained when \( ?_0 \) was changed from 0.17 to 0.25. Total actual transpiration did not change when \( h_{\text{max}} \) was changed from -6000 to -12000 cm. The parameter values for Equation 8 were first assumed to be the same as for the best fit on the experimental data, which were \( h^* = -1000 \) cm, \( h_{\text{max}} = -8000 \) cm, \( p = 1.15 \) and \( ?_0 = 0.17 \). The closest results with the experimental data were obtained by changing only \( h_{\text{max}} \) from -8000 to -7000 cm. These parameter values were used in all
following simulations of $W_1$ and $W_2$ with Equation 8 (Table 2).

Need for slight modification of parameter values obtained from best fit with experimental data can be related to the fact that experimental parameter values were derived from the mean soil water pressure head across the root zone. While in numerical simulation the stress term is calculated for each node and then integrated over the root zone. Table 1 gives a comparison between experimental cumulative actual transpiration and that simulated using the different reduction functions and parameter values listed in Table 2, for the calibration $W_1$ and validation $W_2$ treatments.

### Table 1. Experimental and simulated total actual transpiration for $W_1$ and $W_2$ treatments, using different reduction functions (mm)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Time after the first irrigation (h)</th>
<th>48</th>
<th>96</th>
<th>144</th>
<th>192</th>
<th>240</th>
<th>288</th>
<th>336</th>
<th>384</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp. 5</td>
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<td></td>
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<tr>
<td>Eq. 5</td>
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<td></td>
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<tr>
<td>Eq. 6</td>
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<td></td>
<td></td>
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<tr>
<td>Eq. 7</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Eq. 8</td>
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<td>Exp. 6</td>
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<tr>
<td>Eq. 7</td>
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<tr>
<td>Eq. 8</td>
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<td></td>
</tr>
</tbody>
</table>

### Table 2. Parameter values used in the simulations for different reduction functions

<table>
<thead>
<tr>
<th>Equation</th>
<th>$h_3$ or $h^*$</th>
<th>$h_4$</th>
<th>$h_{50}$</th>
<th>$h_{\text{max}}$</th>
<th>$p$</th>
<th>$\alpha_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>-800</td>
<td>-3500</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>-800</td>
<td>-1800</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>-800</td>
<td>-1600</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>-1000</td>
<td>-</td>
<td>-</td>
<td>-7000</td>
<td>1.15</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Analysis of residual errors, differences between measured and simulated values, can be used to evaluate model performance. These are maximum error $ME$, root mean square error $RMSE$, coefficient of determination $CD$, modeling efficiency $EF$, and coefficient of residual mass $CRM$. The lower limit for $ME$, $RMSE$, and $CD$ is zero. The maximum value for $EF$ is one. Both $EF$ and $CRM$ can be negative. The $ME$ value represents the worst case performance of the model while the $RMSE$ value shows how much simulations overestimate or underestimate measurements. The $CD$ gives the ratio between scatter of simulated values and of measurements. The $EF$ value compares simulated values to average measured values. A negative $EF$ value indicates that the averaged measured values give a better estimate than the simulated values. The $CRM$ is a measure of tendency of the model to overestimate or underestimate measurements. A negative $CRM$ shows a tendency to overestimate. If all simulated and measured data are the same, the statistics yield: $ME = 0$; $RMSE = 0$; $CD = 1$; $EF = 0$; and $CRM = 0$.

### Table 3. Statistical parameters used for comparison of experimental actual transpiration and model performance for the calibration ($W_1$) and validation ($W_2$) treatments

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Equation</th>
<th>$ME$ mm</th>
<th>$RMSE$ mm</th>
<th>$CD$</th>
<th>$EF$</th>
<th>$CRM$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W_1$</td>
<td>Eq. 5</td>
<td>31.27</td>
<td>85.65</td>
<td>0.851</td>
<td>-0.174</td>
<td>-0.087</td>
</tr>
<tr>
<td></td>
<td>Eq. 6</td>
<td>18.26</td>
<td>46.07</td>
<td>0.946</td>
<td>0.053</td>
<td>0.037</td>
</tr>
<tr>
<td></td>
<td>Eq. 7</td>
<td>23.56</td>
<td>70.89</td>
<td>0.952</td>
<td>0.047</td>
<td>0.071</td>
</tr>
<tr>
<td></td>
<td>Eq. 8</td>
<td>28.77</td>
<td>70.03</td>
<td>0.952</td>
<td>0.047</td>
<td>0.071</td>
</tr>
<tr>
<td>$W_2$</td>
<td>Eq. 5</td>
<td>36.24</td>
<td>123.84</td>
<td>0.958</td>
<td>0.041</td>
<td>-0.129</td>
</tr>
<tr>
<td></td>
<td>Eq. 6</td>
<td>31.34</td>
<td>146.56</td>
<td>0.870</td>
<td>-0.148</td>
<td>-0.156</td>
</tr>
<tr>
<td></td>
<td>Eq. 7</td>
<td>35.85</td>
<td>139.23</td>
<td>0.940</td>
<td>-0.063</td>
<td>-0.148</td>
</tr>
<tr>
<td></td>
<td>Eq. 8</td>
<td>30.01</td>
<td>140.40</td>
<td>0.904</td>
<td>-0.242</td>
<td>-0.149</td>
</tr>
</tbody>
</table>
Table 3 presents these statistics for the actual transpiration simulated with different stress functions. This shows that the simulated transpiration for all four equations is quite similar. All the pressure head reduction functions appear to lead to the same result if the required input parameters are specified well. In this case, the results were almost identical because the parameter values were primarily obtained from the same experimental conditions. In such a situation, one can select the simplest function requiring the least parameters in Equation 5.

References


Plastic mulch and drip irrigation effects on Kabocha squash yield and soluble solids content

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Abstract
Kabocha squash, Cucurbita maxima, is an important cash crop for farmers in western Colorado. Combinations of different colored plastic mulches with drip irrigation were compared with non-mulched drip and furrow irrigated kabocha squash for yield, soluble solids concentration on the Brix scale, and water use. An average of 457 mm of water was applied through drip, which was one-fourth the amount applied by furrow irrigation. Drip irrigation in combination with plastic mulch and a transplant method of planting resulted in a greater total yield of squash. Two years average yield was 30.2 ton/ha compared to 12.6 ton/ha for furrow-irrigated squash without mulch. Direct seeded squash without mulch in drip system performed poorly (8.7 ton/ha) compared to transplanting (27.3 ton/ha). After grading the fruits, average marketable yield was 22.1 ton/ha for transplanted squash grown with drip irrigation and mulch cover. Furrow irrigated squash with no mulch differed in yield due to the planting method. Transplanted squash averaged 10.2 ton/ha and direct seeded squash averaged 6.5 ton/ha of marketable squash. Average soluble solids content (measured on the Brix scale) ranged from 11-16 and were consistently higher for drip-irrigated squash compared with furrow irrigated squash. Kabocha yield and soluble solids content were improved under a combination of drip and mulch treatment. Colors of mulch had no effect on soluble solids content or yield.

Key words: Brix, cucurbitaceae, micro-irrigation, water conservation, trickle irrigation

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1 Introduction
Virtually all of the Kabocha squash grown in western Colorado is exported to Japan. Kabocha is a winter squash rich in beta-carotene—a precursor to vitamin A (USDA, 2002). It is prized for its delicious smooth textured flesh. This winter squash has a beautiful jade green rind with celadon green streaks (Fig.1). Its pale orange flesh is tender, smooth and sweet when cooked. Kabocha produced in USA brings a premium price, probably due to its high quality (Anon., 1999). However, to remain competitive, growers need to utilize methods, which can increase production, while maintaining quality and economic viability.

Bhella and Kwolke (1984) reports that summer squash, Zucchini, grown with trickle irrigation and plastic mulch increased plant growth and yield, and reduced the number of days to bloom after planting. The use of plastic mulch and drip irrigation has the possibility to improve winter squash yields and maintain and/or increase quality as well. Feibert et al. (1992) observed improvement in quality from use of plastic mulch due to reduction of warts in winter squash. This resulted in reduced culls and greater marketable squash in eastern Oregon. At the Rocky Ford Research Station in southeastern Colorado, Bartolo (1996) found a significant increase in yield of cantaloupes when grown with plastic mulch and drip irrigation. Drip irrigation with plastic mulch treatment increased muskmelon fruit yield in Matamos, Mexico, as reported by Munguia-Lopez et al. (1994). Lamont et al. (1993) found that a relay crop of muskmelon grown in a Scotch pine Christmas tree field with plastic mulch cover irrigated by drip method produced greater yield and gave higher cash return compared to muskmelon irrigated by drip in bare ground. There are several colored plastic mulches available for horticultural crop production. Tiwari et al. (1998) obtained highest yield for okra using black plastic mulch in combination with drip irrigation in Kharagpur, India. The effect of plastic mulch color on yield of squash has not been reported. Himelrick et al. (1993) used colored
plastic mulch for strawberry. Out of a two-year study the yield for one year was significantly higher for using clear plastic. Our hypothesis was that a combination of drip irrigation and plastic mulch might lead to water savings, greater yield, and higher soluble solids content due to colored plastic mulch.

Fiebert et al. (1992) reported a 50% water savings from use of drip irrigation when compared to furrow irrigation for Kabocha and other winter squash. Water conservation is an important issue in western Colorado, which depends on limited water supplies for use in both urban and agricultural areas. Drip irrigation also provides a flexibility to inject liquid fertilizer at the time when plants need it and according to the amount needed. Lamm et al (1997) reported saving nitrogen applications for corn (Zea mays) using drip system.

Objectives of the study were to see the effect of different colored plastic mulches in combination with drip irrigation on (1) Kabocha squash yield, (2) soluble solids in Brix scale, and (3) water saving compared to producers practice of surface irrigating without mulch. The study also included evaluating planting method (transplanting versus direct seeding) on squash yield.

2 Materials and methods

The study was conducted for three years, 1998-2000, at the Western Colorado Research Center at Rogers Mesa, located 13 km east of Delta, Colorado (latitude: 38° 47’ N and longitude:107° 47’ W). The elevation is 1,715 m above mean sea level. The growing season is approximately 150 days. The soil is classified as Agua Fria Stony Loam (Aridisol) with 3.8% slope. It is a well-drained mesic soil with moderately slow permeability. The field was prepared by diskng followed by roto-tilling. Plastic mulch and drip tape was laid with a Buckeye combination mulch layer drip tape applicator and bed shaper (Buckeye Tractor Co., Columbus Grove, Ohio).

The beds were 1.1 m wide and 2.43 m between centers. The drip tube used for irrigation was T-Tape™ TSX-51030-340 (T-Systems International, San Diego, California). The drip tape was 16mm in diameter 0.25mm (10 mil) in thickness with emitters at 30 cm apart. This tape falls in the high flow rate group with a flow of 340-lph/100 m. The T-Tape was laid 5-7 cm below the surface of the soil in the center of the bed. Kyowa Seed Co. Ltd. of Japan supplied hybrid (variety – Ajihie) seeds (C. maxima x C. maxima) of Kabocha squash. Planting methods used were direct seeding and transplanting. Three different colored plastic mulches were used: 1) clear, 2) black and 3) green. The plastic films were smooth and about 127 cm wide and 38 ?m (1.5 mil) in thickness (manufactured by Flex-Sol, Newark, New Jersey, and supplied by Robert Marvel Plastic Mulch, Harrisburg, PA.).

The research treatments were (a) drip irrigation with clear, green, or black plastic mulch, (b) drip
irrigation with no-mulch, and (c) furrow irrigation with no-mulch on both transplanted and direct seeded squash. Plots were 12 m long with 60 cm in row plant spacing. Row orientation was north to south. The treatments were randomized complete block with a split plot arrangement for planting methods. Individual drip lines were covered with plastic mulch in a random color distribution having a clear, green, black, or no mulch and furrow irrigated row without mulch constituted a block. The block was replicated four times. Individual drip line or furrow irrigated row was divided and one half was directly seeded and the other half was transplanted with 4-week-old seedlings in a split plot arrangement. Total plot number was forty.

Irrigation water was delivered through a series of ditches. Irrigation water from the ditch was first filtered through 4 Amiad™ (manufacturer: Amiad filtration systems, Oxnard, CA.) filters with 0.13 mm openings followed by 2 Spin-Klin™ (manufacturer: Netafim USA, Fresno, CA.) with 0.11 mm openings filters to achieve adequate filtration. The amount of water used was measured with inline flow meters (Neptune T-10 model, 2cm in size, manufactured by Schlumberger Industries, Inc.) for 1999. Flow meters were not available for 1998. Water pressure for 1998 was estimated from emitter flow rate at operating pressure of 62.1 kPa. Water pressure for the drip system was maintained around 62.1 kPa for all years. Soil water status was monitored using tensiometers placed at 30 cm below surface in middle of the bed. Soil water potential was maintained between -15 to -45 kPa, which appears in agreement with recommendation made by Top and Ashcroft (2000).

Irrigation interval for drip-irrigated plots was three days and the furrow-irrigated plots were watered weekly. Soil water level in drip-irrigated plots reached to field capacity -15 to -33 kPa in a relatively short time compared to furrow irrigation, as observed from tensiometer readings. Irrigation amounts depended on estimated evapotranspiration calculated from research center weather station data. Fertilizers were injected using a Chem Feed™ C600P pump (manufacturer: Blue-White Industries, Huntington Beach, CA.). In 1998, 1999 and 2000 approximately 57 liters of UAN (32-0-0) and 80 liters of 5-5-5 (N-P-K) was applied during the growing season.

Seeds and transplants were planted on May 28 – 29 in 1998, June 15-16 in 1999, and June 12-13 in 2000. Squash fruits were harvested in the first week of September in 1998 and the second week of September for 1999. Harvest was not possible in 2000. Squash crop could not mature due to loss of irrigation water in 2000. Squash fruits were individually weighed and evaluated as marketable or non-marketable. Non-marketable squashes were separated based on the following criteria: 1) sunburn, 2) excessive scarring (scarring would include raised warts and ridges on squash surface), 3) too small (< 1 kg), and 3) immature (immaturity was based on greenness of the peduncle (Figure 1). The soluble solid, which consists mostly of sugars, was measured from three squash randomly selected from each plot using Brix scale. The measurements were taken with a hand held refractometer (Atago Co., LTD., Tokyo, Japan).

3 Results and discussion

Depth of irrigation water applied in drip-irrigated plots amounted to 48 cm for the season in 1998 compared to 193 cm for furrow-irrigated plots. Water application by drip irrigation in 1999 slightly improved and an average of 46 cm was applied for the season compared to 208 cm for furrow irrigation. The initial statistical analysis indicate that the crop year was significant for yield and as such yield results of 1998 and 1999 are presented separately in Table 1 and 2. There was significant difference in squash production between drip-irrigated plots with mulch compared to non-mulched furrow irrigated plots (Table 1). Overall yields were lower for furrow-irrigated plots. Transplanted squash tended to produce higher yields compared to direct seeding in drip irrigation treatment. Leskover et al. (2001) obtained similar results for growing muskmelon in southwest Texas, except for a driest season. Fiebert et al. (1992) however, found no advantage from transplanting over direct seeding in their study in eastern Oregon. The increase from transplanting observed in this study may be due to increase in the growing season. Transplanted squash started flowering approximately 20 days before the direct seeded squash plants. In this study the drip irrigated plots with no mulch performed poorly.

Mulch in combination with drip irrigation showed yield improvement (Table 1, 2, and 3). Furrow irrigated plots produced large fruits with low Brix readings in 1998 (Table 1). Brix reading was low for furrow irrigated direct seeded squash for both years (Table 1 and 2). A combination of mulch and drip was significant for Brix level for both 1998 and 1999 (Table 3). Planting method was significant for total and marketable yields for both the years (Table 3). Mulch color and planting method interaction was significant for total and marketable yield in 1999 and similarly planting method was significant for soluble solids (Brix) in 1998 (Table 4). Black plastic with drip irrigation
gave a higher yield for seeded squash in 1999 (Table 2).

Figure 2. Kabocha squash on the left is mature (the peduncle is shriveled or corked and dry). The squash on the right is immature and would be considered non-marketable. The peduncle is still green.

Table 1. Results of Kabocha squash trial 1998 investigating the influence of drip irrigation and plastic mulches at Rogers Mesa Research Center, Hotchkiss, Colorado.

<table>
<thead>
<tr>
<th>Planting Method</th>
<th>Mulch Type</th>
<th>Irrigation Method</th>
<th>Fruit size (kg)</th>
<th>Brix (soluble solids)</th>
<th>Total ton/ha</th>
<th>Marketable ton/ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transplanting</td>
<td>Clear Drip</td>
<td>1.39</td>
<td>14.4</td>
<td></td>
<td>24.6</td>
<td>15.6</td>
</tr>
<tr>
<td></td>
<td>Green Drip</td>
<td>1.47</td>
<td>15.1</td>
<td></td>
<td>28.2</td>
<td>18.3</td>
</tr>
<tr>
<td></td>
<td>Black Drip</td>
<td>1.51</td>
<td>14.1</td>
<td></td>
<td>26.6</td>
<td>18.1</td>
</tr>
<tr>
<td></td>
<td>No Mulch Drip</td>
<td>1.35</td>
<td>13.6</td>
<td></td>
<td>14.1</td>
<td>10.8</td>
</tr>
<tr>
<td></td>
<td>No Mulch Furrow</td>
<td>1.78</td>
<td>12.2</td>
<td></td>
<td>19.3</td>
<td>14.7</td>
</tr>
</tbody>
</table>

| Seeding         | Clear Drip | 1.69              | 13.3            |                       | 22.6          | 16.2             |
|                 | Green Drip | 1.71              | 14.0            |                       | 22.0          | 15.9             |
|                 | Black Drip | 1.73              | 13.7            |                       | 19.1          | 14.9             |
|                 | No Mulch Drip | 1.24         | 11.8            |                       | 7.1           | 4.8              |
|                 | No Mulch Furrow | 1.71          | 11.6            |                       | 16.7          | 7.7              |

Subscript letters following numbers indicate significance of difference between numbers in the same column (at 0.05).
Table 2. Results of Kabocha squash trial 1999 investigating the influence of drip irrigation and plastic mulches at Rogers Mesa Research Center, Hotchkiss, Colorado.

<table>
<thead>
<tr>
<th>Planting Method</th>
<th>Mulch Type</th>
<th>Irrigation Method</th>
<th>Fruit size (kg)</th>
<th>Brix (soluble solids)</th>
<th>Total ton / ha</th>
<th>Marketable ton / ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear Drip</td>
<td>1.30</td>
<td>13.7</td>
<td>37.6</td>
<td>29.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green Drip</td>
<td>1.39</td>
<td>14.4</td>
<td>38.3</td>
<td>34.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Black Drip</td>
<td>1.24</td>
<td>15.5</td>
<td>25.7</td>
<td>16.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Mulch Drip</td>
<td>1.40</td>
<td>16.0</td>
<td>40.5</td>
<td>37.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clear Drip</td>
<td>1.23</td>
<td>14.5</td>
<td>6.8</td>
<td>5.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green Drip</td>
<td>1.26</td>
<td>16.4</td>
<td>18.7</td>
<td>11.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Black Drip</td>
<td>1.43</td>
<td>15.3</td>
<td>35.7</td>
<td>29.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Mulch Drip</td>
<td>1.23</td>
<td>15.8</td>
<td>10.2</td>
<td>8.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Mulch Furrow</td>
<td>0.97</td>
<td>11.0</td>
<td>7.6</td>
<td>5.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Subscript letters following numbers indicate significance of difference between numbers in the same column (at 0.05).

Table 3. Statistical analysis: ANOVA table for randomized complete block with split plot arrangement showing the sources of variation and Pr>F indicating level of significance

<table>
<thead>
<tr>
<th>Fruit size</th>
<th>Brix</th>
<th>Total Yield</th>
<th>Marketable Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year 1998</td>
<td></td>
<td>------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Mulch x Irrigation</td>
<td>0.0006</td>
<td>0.0072</td>
<td>0.0001</td>
</tr>
<tr>
<td>Planting Method</td>
<td>0.0049</td>
<td>0.0041</td>
<td>0.0048</td>
</tr>
<tr>
<td>Mulch x Irrigation x Planting Method</td>
<td>0.0044</td>
<td>0.6262</td>
<td>0.6826</td>
</tr>
</tbody>
</table>

| Year 1999  |       | ------------ | -----------------|
| Mulch x Irrigation | 0.0123 | 0.0015 | 0.0001 | 0.0002 |
| Planting Method | 0.2707 | 0.8973 | 0.0002 | 0.0001 |
| Mulch x Irrigation x Planting Method | 0.0710 | 0.0111 | 0.0002 | 0.0001 |

Table 4. Statistical analysis: ANOVA table for randomized complete block with split plot Arrangement showing the sources of variation for mulch color indicating level of significance

<table>
<thead>
<tr>
<th>Fruit size</th>
<th>Brix</th>
<th>Total Yield</th>
<th>Marketable Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year 1998</td>
<td></td>
<td>------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>Mulch color</td>
<td>0.5315</td>
<td>0.5332</td>
<td>0.2778</td>
</tr>
<tr>
<td>Planting Method</td>
<td>0.0001</td>
<td>0.0226</td>
<td>0.0145</td>
</tr>
<tr>
<td>Mulch color x Planting Method</td>
<td>0.6328</td>
<td>0.6452</td>
<td>0.4356</td>
</tr>
</tbody>
</table>

| Year 1999  |       | ------------ | -----------------|
| Mulch color | 0.9785 | 0.5347 | 0.6443 | 0.9424 |
| Planting Method | 0.4497 | 0.0808 | 0.0349 | 0.0333 |
| Mulch color x Planting Method | 0.1212 | 0.3423 | 0.0089 | 0.0014 |

Mulch Color: Plastic mulch was used with drip irrigation and accordingly dropping furrow irrigation data a separate analysis was performed. The interaction of mulch color for fruit size, soluble solids measure in Brix, total and marketable yields etc. are presented in Table 4. The color of plastic...
mulch appears to have no significant influence on total yield of squash (Table 4).

Acknowledgements
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References

Effect of Polyacrylamide (PAM) on Soil Losses in Furrow Irrigation

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Abstract

Furrow irrigation-induced soil erosion is a serious threat to sustainable irrigated agricultural globally, especially on agricultural lands that are susceptible to erosion and having steep slope. Recently, field studies have demonstrated that small concentration of Polyacrylamide dissolved in irrigation water appreciably reduces soil loss from irrigated furrows and increases net infiltration. In order to study the effect of this material, an experiment was carried out, which employed the fractional method in block design, at the agricultural research station of Tehran University. This experiment included three levels of inflow rate (0.6, 0.8 and 1 lit/sec) and three treatments of PAM (5 ppm, 10 ppm and control) with three replications on no planted lands. Surface soil type of this study area was silt loam. Furrow length was about 140 m with 0.75 m spacing and 1.3% slope. In this experiment, two irrigations were done. In the first one, two different rates of PAM (5 and 10ppm) were added to the stream flow with especial arrangement, then the effect of PAM on soil erosion and infiltration was investigated. In the second irrigation, the stream flow was without PAM, therefore, only the effect of added PAM on the first irrigation on soil erosion and infiltration was followed. In 5ppm treatment, PAM was applied continuously to the stream flow until the stream flow reached to the end of furrow (advance time), then it was intermittently applied to inflow water with half an hour on and off-time. In 10ppm treatment, duration of PAM application was two times of advance time and its application discontinued thereafter. The results of this work showed that the application of 10ppm PAM is suitable for soil loss reduction and infiltration increment. In fact, PAM treatment at 10ppm rate reduced furrow soil losses by 87% and increased net infiltration by 46% as compared to the control treatment. In the second irrigation, which was without PAM, furrow soil loss was reduced by 55% due to carry over effect of PAM from the first irrigation.

Keywords: Infiltration; soil loss; polyacrylamide; furrow irrigation.

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1 Introduction

Research applying polyelectolytes to improve soil physical properties began in the early 1950s, but use of more advanced polyacrylamide (PAM) polymers was not initiated until the last decade. PAM formulations with a wider range of molecular weights, charge types, and densities are now available for agricultural uses. They are more effective, less expensive, and more convenient to use than early polymers (Wallace A. and Wallace, 1966). Thus, they have a greater potential for use in soil management.

PA can be applied to soils as dry granules, broadcast with or without mixing (Terry and Nelson, 1986), and in solution, by spraying (Levy et al., 1991) or diluted in irrigation water (Mitchell, 1986). Application of solution is most efficient and effective (Cook and Nelson, 1986). A subsequent 'curing' or drying period often enhances its soil activity (El-orsey et al., 1991). When applied to the soil surface as a solution, Pam is readily and irreversibly adsorbed to soil particles (Malik et al., 1991b); hence, main effect occurs within 1-5 cm depth (Mitchell, 1986) and perhaps even closer. Most of the applied PAM is apparently bound to external surfaces of soil aggregates (Malik and Letey, 1991). Mitchell (1986) applied 6.6-32.2 kg/ha anionic PAM diluted (150 g/m²) in furrow irrigation water. PAM stabilized the surface soil against dispersion and slaking, and promoted formulation of an more porous depositional seal.

Furrow irrigation subjects smaller surface areas to erosive forces of water than does rainfall or sprinkler irrigation. Therefore, much lower PAM application rates are effective. In furrow irrigated fields study, Lentz et al. (1992) applied minute quantities of PAM to a highly erodible soil. Five to twenty g/m³ anionic PAM (0.5-1.2 kg/ha) was added to irrigation water during the first 40-120 in of inflow. PAM treatments increased net infiltration 10-40% and reduced soil loss 44-99%. Objectives of this work were to (i) determine soil loss reduction, and (ii) assess how PAM effects on infiltration.
2 Methods and materials

This work was conducted on silty loam soil without cultivation in Research Station of Agricultural College at Tehran University. Table 1 shows the soil properties of work are. Surface soil textures were silt loams (18% clay, 54% silt and 28% sand). Study plots were smooth with slope of 1.3%. On the selected plots, pH ranged from 7.6 to 7.8, SAR was 0.65 to 0.85, EC varied from 0.61 to 0.84 dS/m. Slope was 1.3%.

Seedbeds were disked or moldboard plowed, the roller-harrowed. After land preparation, furrows were made in V shape having 0.75 m wide and 140 m length. Irrigation water EC was 0.8 dS/m, and pH was 7.4. Water distribution and PAM injection systems are shown on Figure 1.

![Figure 1: Schematics of water supply and PAM injection systems](image)

Table 1. Soil properties

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Soil Depth (cm)</th>
<th>FC by Weight (%)</th>
<th>PWP by Weight (%)</th>
<th>Soil Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-20</td>
<td>22.3</td>
<td>12.6</td>
<td>Silt loam</td>
</tr>
<tr>
<td>2</td>
<td>20-40</td>
<td>23.0</td>
<td>12.9</td>
<td>Silt loam</td>
</tr>
<tr>
<td>3</td>
<td>40-60</td>
<td>22.8</td>
<td>11.9</td>
<td>Loam</td>
</tr>
<tr>
<td>4</td>
<td>60-80</td>
<td>22.8</td>
<td>11.8</td>
<td>Sand loam</td>
</tr>
<tr>
<td>5</td>
<td>80-100</td>
<td>22.0</td>
<td>10.8</td>
<td>Sand loam</td>
</tr>
</tbody>
</table>

Furrow infiltration and soil loss studies employed factorial randomized block designs with three replications. Three inflows (0.6, 0.8 and 1.0 lit/sec) and two levels of PAM were used in this work. A granular PAM was used to prepare 5 ppm and 10 ppm PAM irrigation water. These levels of inflows were determined through maximum erodible inflow, which found to be 0.6 lit/sec for this soil. Experiment included two irrigations where in the first one PAM was added to irrigation water and the second one was without PAM addition. PAM application strategies were varied during experimentation. Treatments for this work was as follow:

- Control (irrigation without PAM).
- Five gram PAM was added to every cubic meter irrigation water during advance time (time required for water to advance to end of
furrow). Then PAM was added to irrigation intermittently (half an hour on and off time) on the rest of application time.

Ten gram PAM was added to every cubic meter irrigation water on the length of two times of advance time (30 min). Then no PAM was added to irrigation on the rest of irrigation time.

Irrigation application time for the first irrigation was two and half an hour in order to replace soil deficit moisture on the first 30 cm depth. In the first irrigation, erosion and infiltration were measured two times. Inflow-outflow method was used to measure total infiltration. Flow measuring device used was WSC flume Type I. Then infiltration on furrow with PAM was compared with the infiltration on the control furrow. To measure soil losses, one-liter size samples were taken from the furrow end on the different time. Samples were dried and weighed to determine sediment concentration in one-liter water. Then through runoff hydrograph total soil losses was determined from each furrow. Irrigation application time for the second irrigation was set to be five and half hours in order to determine carry over effect of PAM that was added on the first irrigation.

3 Results and discussion

Experiment related to First Irrigation- addition of PAM in irrigation water caused increment of advance time that is shown on Figure 2. Ten ppm PAM caused the most increment on advance time for each level of inflow. This would reduce high leaching potentials that now occur at furrow heads and also improve in-field crop productivity. Results of soil losses reduction were shown on Figure 3. For inflow of 0.6 lit/sec sediment losses was increased for the first twenty minute for the control treatment and then it slightly decreased as furrow became stable and sediment concentration reached 12 gr/lit as shown on Fig. 3. As inflow increased, sedimentation concentration also increased which indicates inflow effect. When PAM level was 5 ppm with intermittent addition of PAM, sediment losses went up to 8 gr/lit after 30 minutes for 0.6 lit/sec, then it was reduced to almost zero after 30 min. This pattern was repeated itself for the rest of irrigation time as shown in Figure 3. This trend is the same for the other inflow levels with the same concentration of PAM. When PAM level was 10 ppm and the addition of PAM was continuous for duration of two times of advance time, sediment losses increased up to 3 gr/lit at the end of irrigation time for 0.6 lit/sec. This trend is similar to the other inflow levels with the same concentration of PAM. Figure 4 shows the soil losses reduction with the use of PAM in compare to control. It indicates that the most soil loss reduction (98%) is related to inflow level of 0.6 lit/sec with 10 ppm PAM. The least amount (70%) is related to inflow level of 1.0 lit/sec with 5 ppm PAM. Near elimination of soil loss ensures retention of valuable fertilizer and pesticide amendments, maintains field productivity, and reduces the need for costly remediation efforts on eroded fields. Figure 5 indicates total infiltration caused by PAM. Results obtained showed that total infiltration was increased due to PAM. When inflow level was 0.6 lit/sec, increment of total infiltration was 91 and 74 percent for PAM levels of 10 and 5 ppm, respectively. Increased infiltration permits shorter irrigations, especially on steeply sloping fields. Statistical analysis showed that the effect of inflows and PAM levels and their interaction on soil losses and total infiltration was significant at 1% probability level.

Experiment related to Second Irrigation- In order to find out the effect of remaining PAM on soil losses, irrigation water used on the second irrigation was without PAM. Soil loss reduction is show in Figure 6. The most reduction was when inflow was 0.6 lit/sec having 10 ppm PAM. The least reduction was when inflow was 1.0 lit/sec having 5 ppm PAM. Compared with control furrows, it reduced soil loss by 66 and 44 percent, respectively, on the above mentioned cases. As inflow becomes less, soil reduction losses increases. Results of this study were similar to works done by the other researchers.
Figure 2. Advance rates in different PAM-treated furrows with different inflow compared with control.
Figure 3. Sediment concentration from furrow end during irrigation time in PAM-treated furrows with different inflows compared with control
Figure 4. Soil loss reduction under different PAM-treated furrows with three inflows compared with control in the first irrigation.

Figure 5. Soil infiltration increment in different PAM-treated furrows with three inflows compared with control in the first irrigation.
4 Conclusions
The result obtained from the first irrigation showed that 10-ppm PAM had the most effect on the advance time increment. It also reduced soil losses from furrow in a significant amount. From standpoint of soil erosion reduction losses, 10 and 5 ppm PAM with different levels of inflow reduced an average 91% and 82%, respectively. From standpoint of total infiltration increment, 10 and 5 ppm PAM with different levels of inflow increased infiltration an average 54% and 36%, respectively. Using 6.9 and 2.3 kg PAM with inflow of 0.6 lit/sec caused about 0.06 and 0.24 ton/ha soil losses, respectively. Using 6.9 and 2.3 kg PAM with inflow of 0.8 lit/sec caused about 0.42 and 0.94 ton/ha, respectively. When inflow was 1.0 lit/sec with using 6.9 and 2.3 kg PAM caused about 1.6 and 2.7 ton/ha soil losses, respectively. In the second irrigation, which was without addition of PAM, soil erosion reduction losses were an average 59 and 52 percent, respectively.

5 Acknowledgements
The authors wish to thank Tehran University for its financial support.

References

Modeling water uptake under alternate-furrow irrigation

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Abstract
Root water uptake in soils was simulated for different alternate furrow irrigation practices, as well as for conventional furrow irrigation (EFI). In one form of alternate furrow irrigation practice, irrigation is fixed in one of the two neighboring furrows (FFI). Otherwise, irrigation is alternated between two neighboring furrows during consecutive irrigation periods (AFI). Simulations were conducted for two soil types, clay loam and loamy sand. Several levels of irrigation water application and either 0.4 or 1 m root depth were used. With the same irrigation time, water applied was reduced nearly by half for AFI and FFI, compared with EFI. Water uptake was reduced by 30.6% for AFI and by 33.9% for FFI, relative to EFI for a clay loam with 0.4 m rooting depth. About 20% water uptake reduction might be expected for AFI and EFI with 1 m rooting depth. For loamy sand, the largest water uptake reductions of AFI and FFI were about 60% and 70%, when rooting depths were 0.4 and 1 m respectively. There were no significant differences of application efficiency predicted for the three irrigation methods used with clay loam, based on similar water amounts being applied. For loamy sand, the EFI appeared to achieve the highest application efficiency. Predictions for the two alternating irrigation methods suggested higher leaching losses than the EFI for the both soils at the lower irrigation levels, with the leaching losses tending to be similar at the higher irrigation levels.

Key words: Alternate furrow irrigation; simulation; water uptake; application efficiency.

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1 Introduction
Furrow irrigation is the most commonly used irrigation method in arid and semi-arid regions. Furrow irrigation often leads to leaching of fertilizers and pesticides to ground water due to over-irrigation. At present, furrow irrigation is one of the main contributors to ground water NO$_3^-$ pollution. For a 300 mm irrigation of clay loam, as much as 40% of the available NO$_3^-$ could be lost from the root zone (Artiola, 1991). Most of these NO$_3^-$ losses occurred on the two-thirds of the field closest to the irrigation source and no significant NO$_3^-$ losses were measured on the one third of the field farthest from the water source. Methods have been developed to improve application efficiency and to reduce water and solute leaching of the conventional furrow irrigation. Wide-spaced furrow irrigation or skipped crop rows during irrigation have been investigated by many researchers (Musick and Dusek, 1974, 1982; Stewart et al., 1981; Crabtree et al., 1985; Hodges et al., 1989; Graterol et al., 1993; Stone and Nozziger, 1993). Fixed alternate-furrow irrigation (FFI), that is, irrigation was always given to a fixed one of two neighboring furrows, reportedly caused small yield loss of sugar beet, sorghum, and potato compared with every-furrow irrigation (EFI), but irrigation water amount decreased by 30-50% (Musick and Dusek, 1974). Kang et al. (1997a) proposed a modified alternate furrow irrigation (AFI), in which one of the two neighboring furrows was alternately irrigated during consecutive irrigations. Kang et al. (2000) also reported that AFI could maintain high grain yield with up to 50% reduction in irrigation amount, whereas both FFI and EFI showed a substantial decrease of yield with reduced irrigation amount.

For high yield and minimum leaching, it is important to quantify effects of alternate irrigation on solute leaching and crop yield. In light of high costs of field experiments, a low cost means of studying water flow and solute transport in irrigation fields is through numerical modeling. Water and solute movement for EFI and FFI has been investigated using a two-dimensional water and solute movement model (Benjamin et. al, 1994). Based on CHAIN_2D (Simunek and van Genuchten, 1994), CHAIN_IR was developed to simulate movement of water, heat, and multiple solutes in unsaturated soils (Zhang, 1995). Various irrigation systems can be simulated, including flood, furrow, sprinkler, and drip irrigations. In this study, CHAIN_IR is used to simulate water flow and root uptake under alternate furrow irrigation systems. The overall objectives of this research are to study water and solute movement in soils with root uptake under both alternate furrow irrigation and
conventional furrow irrigation.

2 Materials and methods

CHAIN_IR numerically solves the Richards’ equation for water flow and the convection-dispersion equation for solute transport using the Galerkin-type linear finite-element scheme. The governing equation for two-dimensional water flow is as follows:

\[
S(h) \frac{\partial^2 h}{\partial t} + \frac{\partial}{\partial x_j} \left[ K \left( K_{ij} \frac{\partial h}{\partial x_j} \right) \right] = S
\]

where \( \partial \) is the volumetric water content, \( h \) is the pressure head, \( x_j \), \( i = 1,2 \), are the spatial coordinates, \( t \) is time, \( S \) is the sink term, \( K_{ij} \) are components of a dimensionless anisotropy tensor, and \( K \) is the unsaturated hydraulic conductivity function. The anisotropy tensor is used to account for an anisotropic medium. For an isotropic medium, the diagonal entries of \( K_{ij} \) equal one and the off-diagonal entries are zero. Unsaturated soil hydraulic functions \( K \) are described by a set of closed-form equations (van Genuchten, 1980):

\[
S_e(h) = \left( \frac{\partial \theta_e}{\partial \theta_s} \right)^{1/n} \left( 1 - \frac{\theta}{\theta_s} \right)^{1 + (1 - n)/n}
\]

where \( n = 1 - 1/m, n > 1 \) and

\[
K = K_s S_e^{1/2} \left[ \left( 1 - S_e^{1/m} \right)^{-1} \right]^{1/2}
\]

in which \( \partial \) and \( \theta \) denote the residual and saturated water contents, respectively, \( n \) and \( a \) are retention parameters, and \( K_s \) is the saturated hydraulic conductivity. In this study, two soils of clay loam and loamy sand texture were represented, and their hydraulic parameters are presented in Table 1.

The sink term in Equation (1) represents the volume of water removed per unit time from a unit volume of soil due to plant water uptake. To account for effects of water stress, \( S \) is defined as follows

\[
S(h) = \frac{1 - \frac{\theta}{\theta_s}}{\frac{\theta}{\theta_s}}
\]

where \( S_p \) is the potential water uptake rate and \( h_{50} \) is the matric pressure at which \( S \) is reduced by 50%. In this work, \( h_{50} \) is \( \sim 2000 \text{ cm and } 600 \text{ cm for the clay loam and the loamy sand, respectively.} \)

To simulate water and solute transport under field irrigation conditions, \( \text{CHAIN}_\text{IR} \) was modified so that boundary conditions could be switched back and forth between evaporation and irrigation inputs. Simulations were performed in a two-dimensional vertical plane (see Figure 1 for the geometry). The following initial conditions were applied to all simulations. A region of 25 \( \times \) 40 m was assumed to be subjected to root uptake with a maximum transpiration rate of 0.45 cm d\(^{-1}\), excluding a 2 cm surface layer. The potential evaporation rate was 0.3 cm d\(^{-1}\). An initial soil water pressure head was used everywhere in the soil profile, -800 cm for the clay loam and -500 cm for the loamy sand, respectively. The boundary conditions were different for different irrigations. At the top of the study domain, the boundary conditions vary with different irrigation methods and change with time. During irrigation, \( h(x, 120, t) = 3 \text{ cm (along AB and CD for EFI), } h(x, 120, t) = 3 \text{ cm (along AB for FF1), } h(x, 120, t) = 3 \text{ cm (alternated along AB or CD for AF1). AB and CD are half widths of the furrows. The part of boundary that had not been covered during irrigation and the boundary along AD without irrigation are subject to evaporation. Actual surface evaporation flux is calculated internaly by the program. See Simunek and van Genuchten (1994) for details. For the two sides of the domain, zero flux conditions were used because of the symmetry for all three irrigation methods \( q(x, 0, z, t) = 0, q(x, 50, z, t) = 0 \). At the bottom, a unit hydraulic gradient boundary condition was used for the irrigation methods \( q(x, 0, z, t) = K(h) \) in which \( q \) is water flux across the boundary. For clay loam, there were 4 irrigations in total, each with a 10-day interval during a 50-day simulation period. The first irrigation was on the 10\text{th} day. While there were 5 irrigations in total with the first on the first day for the loamy sand.

Table 1. Soil hydraulic parameters

<table>
<thead>
<tr>
<th>Soil</th>
<th>( \theta_s )</th>
<th>( \theta_r )</th>
<th>( \theta_s ) (g cm(^{-1}))</th>
<th>( K_s ) (cm d(^{-1}))</th>
<th>( a ) (cm)</th>
<th>( n )</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay loam</td>
<td>0.46</td>
<td>0.107</td>
<td>1.30</td>
<td>15.5</td>
<td>0.0208</td>
<td>1.28</td>
<td>Kang et al. (1997b)</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>0.37</td>
<td>0.04</td>
<td>1.33</td>
<td>146.6</td>
<td>0.0588</td>
<td>1.65</td>
<td>Benjamin et al. (1994)</td>
</tr>
</tbody>
</table>
3 Results and discussion

Simulated scenarios include combinations of the three irrigation methods, different irrigation levels and two root depths. Results showed that the applied water for AFI and FFI was reduced by nearly a half compared with EFI for the same irrigation time, while there was no significant difference between AFI and EFI. With less water being applied, so root water uptake for AFI and FFI was generally reduced. However, the extent of the reduction was less than half. Table 2 presents the percentage reduction of applied water and root water uptake under AFI and FFI for the clay loam, when the irrigation time was the same as for EFI. The percentage reduction of irrigation and water uptake was calculated by

\[
IR = \frac{I_e - I_a}{I_e} \times 100\% \\
WR = \frac{Re - Ra}{Re} \times 100\%
\]

(5)

where \(IR\) and \(WR\) are percentage reduction of irrigation water and root water uptake, respectively, \(I_e\) and \(Re\) are irrigation water and water uptake for every furrow irrigation, \(I_a\) and \(Ra\) are irrigation water and water uptake for alternate irrigations of AFI and FFI. For 0.4 m root depth, percentage reduction of root water uptake decreased from 30.6 to 2.8% for the AFI, and from 33.9 to 3.5% for the FFI with the irrigation increased, while the applied water reduced by average 48.1% for the AFI and 49.7% for the FFI. With root depth of 1 m, root water uptake reduction was between 14.0 and 20.8% for the AFI, and between 10.4 and 19.3% with similar applied water reduction. With the shallower root depth, the reduction percentage of water uptake for the AFI and FFI decreased with increasing water applied. This was also could be demonstrated by Figure 2, which shows water uptake with the different irrigation levels under the three irrigation methods for the two root depths. Water uptake easily reached its maximum under the EFI for the clay loam, that is, water uptake would not increase any more with more water applied, whereas water uptake gradually increased for the AFI and EFI with the root depth of 0.4 m (Figure 2A). When root depth was 1 m, water uptake increased continuously with increasing irrigation time for the three irrigation methods, and the difference of water uptake between the EFI and the two alternative irrigation systems remained (Figure 2B). These results suggested that for the clay loam with a shallow root distribution, water could be wasted easily under the EFI if irrigation time was not carefully controlled and the alternative irrigation methods should be a better option to reduce water amount applied and help to reduce the potential risk of irrigation water moving into ground water. Simulated results for the loamy sand are presented in Table 3 and Fig. 3. The larger reduction percentage of water uptake was found for the loamy sand with similar irrigation water reduction. With the root depth of 0.4 m, the root uptake reduction declined from 58.1 to 19.1% for AFI with an average 47.0% irrigation reduction, and 63.4 to 20.2% for FFI with an average 47.0% irrigation reduction with the root depth of 1 m, the largest reduction of water uptake was 68.3 and 71.0% at the lowest irrigation level for the AFI and FFI, respectively. The alternative irrigation methods may not be appropriate with lower irrigation levels for the loamy sand because the reduction percentage of water uptake was greater than of irrigation water. The results in most of simulated conditions that water uptake reduction was less than the reduction of irrigation water suggested that the AFI and EFI could be one of alternatives to achieve optimal profit (yield/water consumption), rather than the maximum yield in the agricultural practices.
Table 2. Simulated water intake and root uptake reductions (%) for AFI and FFI, compared with EFI, for clay loam with various irrigation durations

<table>
<thead>
<tr>
<th>Soil depth (cm)</th>
<th>Irrigation time (d)</th>
<th>AFI</th>
<th>FFI</th>
<th>EFI</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>0.3</td>
<td>46.2</td>
<td>50.0</td>
<td>50.0</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>48.1</td>
<td>49.8</td>
<td>49.8</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>48.1</td>
<td>49.5</td>
<td>49.5</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>48.6</td>
<td>49.5</td>
<td>49.8</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>48.5</td>
<td>49.8</td>
<td>49.5</td>
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<tr>
<td></td>
<td>1.2</td>
<td>48.9</td>
<td>49.5</td>
<td>49.5</td>
</tr>
<tr>
<td></td>
<td>1.6</td>
<td>48.9</td>
<td>49.5</td>
<td>49.5</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>48.9</td>
<td>49.5</td>
<td>49.5</td>
</tr>
<tr>
<td>100</td>
<td>0.3</td>
<td>46.1</td>
<td>50.0</td>
<td>50.0</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>48.1</td>
<td>49.8</td>
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<tr>
<td></td>
<td>0.6</td>
<td>48.1</td>
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<td></td>
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<td>48.5</td>
<td>49.8</td>
<td>49.5</td>
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<tr>
<td></td>
<td>1.2</td>
<td>48.9</td>
<td>49.5</td>
<td>49.5</td>
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<tr>
<td></td>
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<td>48.9</td>
<td>49.5</td>
<td>49.5</td>
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<tr>
<td></td>
<td>2.0</td>
<td>48.9</td>
<td>49.5</td>
<td>49.5</td>
</tr>
</tbody>
</table>

Figure 2. Root water uptake as affected by irrigation duration for clay loam with (A) 0.4 m and (B) 1 m root depths
Table 3. Simulated water intake and root uptake reductions (%) of AFI and FFI, compared with EFI, for the loamy sand with various irrigation durations

<table>
<thead>
<tr>
<th>Root depth (cm)</th>
<th>Irrigation time (d)</th>
<th>AFI</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.3</td>
<td>44.5</td>
<td>45.4</td>
<td>45.6</td>
<td>47.4</td>
<td>47.5</td>
<td>48.1</td>
<td>48.6</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>58.1</td>
<td>53.8</td>
<td>48.0</td>
<td>38.1</td>
<td>29.0</td>
<td>23.6</td>
<td>22.0</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>44.2</td>
<td>45.0</td>
<td>46.4</td>
<td>47.5</td>
<td>47.5</td>
<td>48.3</td>
<td>48.9</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>68.3</td>
<td>67.1</td>
<td>64.7</td>
<td>54.8</td>
<td>42.8</td>
<td>34.3</td>
<td>26.9</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>1.2</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>1.6</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>Irrigation reduction</th>
<th>Root uptake reduction</th>
<th>Irrigation reduction</th>
<th>Root uptake reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>44.2</td>
<td>68.3</td>
<td>44.2</td>
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</tr>
<tr>
<td>0.1</td>
<td>45.0</td>
<td>67.1</td>
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<tr>
<td>0.2</td>
<td>46.4</td>
<td>64.7</td>
<td>46.4</td>
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<tr>
<td>0.3</td>
<td>47.5</td>
<td>54.8</td>
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<tr>
<td>0.4</td>
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<td>42.8</td>
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<tr>
<td>0.5</td>
<td>48.6</td>
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</tr>
<tr>
<td>0.6</td>
<td>48.7</td>
<td>26.9</td>
<td>48.7</td>
<td>26.9</td>
</tr>
</tbody>
</table>

Figure 3. Root water uptake for different irrigation durations for loamy sand with of (A) 0.4 m and (B) 1 m rooting depths

Figure 4 presents irrigation application efficiency (AE) values for different irrigation amounts for clay loam with different rooting depths, where AE is defined as water uptake divided by total irrigation water applied. There was no significant difference of AE with similar water amounts applied under simulated conditions for the three irrigation methods, which suggested that reducing irrigation time by a half would produce very similar results with alternative irrigation methods for clay loam in terms of water uptake. The AE’s under different conditions for loamy sand are shown in Figure 5. EFI appeared to produce higher application efficiency than AFI and FFI, especially when rooting depth was 0.4 m, while there were no significant differences between AFI and FFI. So, regarding application efficiency, the alternate irrigation methods might not be a good choice for loamy sand. Simulation results were generally consistent with previous field research, which showed that alternate irrigation practice appeared to result in slightly lower irrigation efficiency on sandy loam (Rice et. al, 2001). However, Kang et
al. (2000) reported that the AFI had much higher irrigation application efficiency than the FFI and EFI, with lower irrigation amounts. They attributed the advantage of AFI over FFI and EFI to root physiological response to the drying environment by regulating stomatal opening and reducing leaf transpiration. These factors were not accounted for in this study and more research is needed to understand integrated effects of alternate irrigation on plant systems.

One major concern about alternate irrigation methods was that they might cause more leaching than the conventional furrow irrigation. Figures 6 and 7 show the water leaching fractions under different simulation conditions for clay loam and loamy sand, respectively. Leaching fraction is defined as total soil water passing beyond the root zone after a 50-day simulation divided by the total irrigation applied. For both clay loam and loamy sand, leaching amounts increased as irrigation water increased. For clay loam, FFI generally resulted in the highest leaching fraction. The leaching fraction was higher for AFI than for EFI when irrigation amounts were lower than 30 cm (about 80% ET). However, as the irrigation amount increased, EFI had similar leaching to FFI and higher leaching than AFI. Figure 8 shows temporal changes in soil water potential distributions under different irrigation methods for a 40-cm rooting depth. Water moved noticeably deeper for FFI than for AFI and EFI.
during the earlier simulation period. During later periods, it seems that water moved downwards slower for alternate irrigation than for EFI. Simulations up to 25, 40.5 and 50 days showed the wetting front for FFI moving to 74, 85 and 94 cm depths, to 64, 78 and 88 cm for AFI, and to 63, 82 and 94 cm for EFI. It appears that water lateral movement during the later period might prevent water moving deeper for alternate irrigations, whereas more uniform water distribution under EFI facilitates deeper water movement. When rooting depth was 1 m, there was no leaching for clay loam. As expected, loamy sand produced much higher leaching than clay loam. Alternate irrigation methods resulted in higher leaching fractions than EFI for both rooting depths, which was consistent with results of lower AE’s for AFI and FFI. When rooting depth was 0.4 m, FFI resulted in higher leaching fractions than AFI at lower irrigation levels. With increasing applied water, leaching percentage tends to be the same for the three irrigation methods. Figure 9 shows distributions soil water potential for loamy sand with 0.4 m rooting depth. At the lower irrigation level, the wetting front moved deeper for AFI and FFI than for EFI, while there were no significant differences between AFI and FFI. Given the lower AE and higher leaching for alternate irrigation methods, AFI and FFI may not be good options for irrigation of loamy sand. The simulation results did not clearly show the advantages of alternating irrigation systems as some research suggests. Many factors may contribute to the disparity, such as soil properties, fertilizer availability, plant types and others.

Figure 6. Water leaching fraction of different irrigation amounts for clay loam with 0.4 m rooting depth

Figure 7. Water leaching fraction of different irrigations for the loamy sand with root depths of A) 40 cm and B) 100 cm
Figure 8. Temporal distributions of water pressure in 0.4 m rooting depth for clay loam when irrigation was about 100% ET at 25, 40.5 and 50 day (from left to right)
Figure 9. Temporal distributions of water pressure in 0.4 m rooting depth for loamy sand when irrigation was about 50% ET at 25, 40.5, and 50 day (from left to right)
4 Conclusions

Numerical simulations were conducted to study water and root water uptake in soils using alternate furrow irrigation (AFI) and fixed furrow irrigation (FFI), as well as conventional every-furrow irrigation (EFI). With the same irrigation time, compared with EFI, water applied was reduced by nearly a half for AFI and FFI while water uptake was reduced by less than 35%. A reduction of about 20% water uptake was found for AFI and EFI with a 1-m root depth. AFI and EFI could be alternatives to achieve optimal profit based on yield/water consumption, rather than maximum yield in agricultural practices for clay loam. For loamy sand, the largest water uptake reduction of AFI and FFI was about 60% with a 0.4 m root depth and 70% with a 1-m root depth. There were no significant differences of application efficiency for the three irrigation methods on clay loam with similar water applications. For loamy sand, EFI resulted in the highest application efficiency. The two alternate irrigation methods resulted in higher leaching fractions than EFI for both soils, and leaching fractions tended to be similar at the higher irrigation levels. Caution is recommended in adopting AFI and FFI on soils with higher hydraulic conductivity because water could easily leach out of the soil profile.

References


Scheduling drip irrigation of young mango crop by tensiometer

Pramod Kumar Singh, Kamla Kant Singh and Kamal Narayan Shukla

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Abstract
A field experiment was conducted to evaluate the response of five years old mango crop (Mangifera indica Linn) to irrigation scheduling at different soil tensions, when using drip irrigation and black polyethylene mulch. Resulting water requirements and fruit yield were determined when the crop was grown under the typical tarai condition of Uttaranchal (India). Tensiometers were used to automatically schedule irrigation wherever soil tension reached 20, 30 or 60 kPa. A significant increase in final fruit retention and marketable fruit yield was observed in drip irrigation and drip irrigation with back polyethylene mulched treatments. The highest fruit retention of 453 fruit per tree and fruit yield of 76.33 kg per tree were obtained from the treatments irrigated at 20 kPa tension under drip irrigation with mulch. However, water use efficiency was observed a maximum for the treatment irrigated at 60 kPa tension. Water was applied after flower bud development until maturity during the months of February, March, April and May. The applications varied from 180 to 1544, 135 to 1180 and 90 to 800 litres per plant in the treatments irrigated at 20, 30 and 60 kPa soil tension, respectively. In contrast, water applied in surface irrigation treatments was 600, 1150 and 1810 litres per plant, respectively, in the month of March, April and May.

Key words: Drip irrigation Scheduling, Tensiometer, Mango

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1 Introduction
India has made good progress in the horticultural map of the world with total annual production of horticultural crops touching over 149 million tonnes during 1999-2000. The horticultural crops cover about 9% of the total area contributing about 24.5% of gross agricultural output in the country. Today India is the second largest producer of fruits (46 million tonnes), which is 10% of the total fruit production of the world (Negi, 2001). Mango is one of the important fruit crops of India and occupies 37.3% of total fruit crop area, producing 23% (10.5 million tonnes) of total fruit production. However, productivity is only 7.1 tonnes per ha which is significantly low compared to other mango growing countries.

Despite mango being considered a drought resistant crop, it benefits from supplementary irrigation when the rainfall is limited or poorly distributed. It’s believed that at least 700 mm of well distributed rainfall is necessary throughout the year for commercial cultivation of mango crop, but heavy rains around flowering time are detrimental (Galan Saevo, 1990). Most researchers have reported that water requirement of the mature mango orchard is about 1000 mm per year and a degree of stress during flower bud development is advantageous (Cull, 1989; Larson and Scaffer, 1989). Drip irrigation is today applied successfully to many horticultural crops. Mango appears to be well adapted to this method but further research is required to determine optimal water requirements and irrigation scheduling under a variety of drip irrigation and mulched conditions. In spite of mango being an important fruit crop, there is little literature available regarding its water requirements, fertilizer and irrigation scheduling. The primary objective of this investigation was to determine seasonal water requirements during the fruit development stages of a young mango crop under drip irrigation and mulched conditions. Soil moisture regimes under drip or surface irrigation, in combination with plastic mulching, were also investigated to determine effects on fruit yield and fruit parameters of mango.

2 Materials and methods
2.1 Experimental details
The field experiment was conducted on five years old Dasherahi mango (Mangifera indica Linn) on a 10 m x 10 m spacing at the Horticulture Research Centre of G. B. Pant University of Agriculture and Technology, Pantnagar (India). The site is located at 243.8 m altitude, 29°N latitude and 79.3°E longitude in humid subtropical climate in the tarai region of Uttaranchal.
The soil is sandy loam with a bulk density of 1.46 g/cc and field capacity of 18.7% by weight. The experimental design consisted of 8 treatments (Table 1) having three plants per treatment and three replications. Each plant was provided with four drippers of 8 litres per hour capacity, spaced at 75 cm on either side of the plant stem on 16 mm LDPE lateral lines. The laterals were supplied by 50 mm PVC sub-main lines. Drippers were operated at a pressure of 1.2 kg/cm$^2$. LDPE black plastic mulch of 100-micron thickness was laid to restrict soil evaporation.

Table 1. Details of drip and surface irrigation of mango crop

<table>
<thead>
<tr>
<th>Irrigation Treatment</th>
<th>Details of irrigation and mulching treatments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without mulch</td>
<td></td>
</tr>
<tr>
<td>DI$_1$</td>
<td>Drip irrigation at 20 kPa soil matric tension</td>
</tr>
<tr>
<td>DI$_2$</td>
<td>Drip irrigation at 30 kPa soil matric tension</td>
</tr>
<tr>
<td>DI$_3$</td>
<td>Drip irrigation at 60 kPa soil matric tension</td>
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<tr>
<td>SI$_4$</td>
<td>Surface irrigation without mulch or control (SI) at 50% level of available soil water depletion (AWD)</td>
</tr>
<tr>
<td>With 100 micron black plastic mulch</td>
<td></td>
</tr>
<tr>
<td>DIM$_5$</td>
<td>Drip irrigation at 20 kPa soil matric tension + plastic mulch</td>
</tr>
<tr>
<td>DIM$_6$</td>
<td>Drip irrigation at 30 kPa soil matric tension + plastic mulch</td>
</tr>
<tr>
<td>DIM$_7$</td>
<td>Drip irrigation at 60 kPa soil matric tension + plastic mulch</td>
</tr>
<tr>
<td>SIM$_8$</td>
<td>(SIM) at 50% level of available water depletion (AWD) + plastic mulch</td>
</tr>
</tbody>
</table>

2.2 Soil matric-tension based real-time drip irrigation scheduling of mango

Irrigation scheduling was based on real time feed back from tensiometers installed in the effective plant root zone, through automated drip irrigation system. Vacuum gauge magnetic switching tensiometers were used to automatically schedule irrigation by opening solenoid valves on demand when the soil matric tension reached threshold values of 20, 30 or 60 kPa. Two tensiometers were installed per treatment and wired in parallel so that either one of the two could initiate irrigation. The tensiometers were placed at 60-cm depth, 100 cm from plant stem. The tensiometer stops irrigation when soil matric tensions reach 10, 20 or 50 kPa. Hence, moisture maintained in the treatments were in the ranges 10-20, 20-30, and 50-60 kPa soil matric tensions. To see the response to mulching, each level of irrigation was also combined with a black plastic mulch of 100-micron thickness.

3 Results and discussion

3.1 Fruit retention and fruit yield

Fruit retention and yield of mango were recorded for the different irrigation and mulching treatments.

**Fruit retention:** Table 2 presents the fruit retention data for different stages of fruit development in March, April and May. Average number of fruit set per panicle was 80.3, 7.67 and 6.33 at mustard, marble and maturity stages, respectively, in the plot irrigated at 20 kPa soil matric tension under drip irrigation combined with plastic mulching. In contrast fruit retention was 31, 2.33 and 1.33 fruits per panicle at the same stages of fruit development for surface irrigation at the 50% level of available soil moisture depletion.

Table 2. Effect of irrigation at different soil matric tensions on fruit (set) retention of mango

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Fruit set/penicle at mustard stage</th>
<th>Fruit set/penicle at marble stage</th>
<th>Fruit set/penicle at maturity stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>DI$_1$</td>
<td>72.0</td>
<td>5.33</td>
<td>5.00</td>
</tr>
<tr>
<td>DI$_2$</td>
<td>66.0</td>
<td>4.33</td>
<td>3.67</td>
</tr>
<tr>
<td>DI$_3$</td>
<td>43.7</td>
<td>3.33</td>
<td>2.33</td>
</tr>
<tr>
<td>SI$_4$</td>
<td>31.0</td>
<td>2.33</td>
<td>1.33</td>
</tr>
<tr>
<td>DIM$_5$</td>
<td>80.3</td>
<td>7.67</td>
<td>6.33</td>
</tr>
<tr>
<td>DIM$_6$</td>
<td>69.7</td>
<td>6.67</td>
<td>5.66</td>
</tr>
<tr>
<td>DIM$_7$</td>
<td>60.3</td>
<td>5.33</td>
<td>2.83</td>
</tr>
<tr>
<td>SIM$_8$</td>
<td>37.0</td>
<td>3.33</td>
<td>1.66</td>
</tr>
</tbody>
</table>

**CD at 5%**

<p>| Mulch irrigation treatment | Fruit set/penicle at maturity stage |</p>
<table>
<thead>
<tr>
<th>CD at 5% Mulch irrigation treatment</th>
<th>Fruit set/penicle at maturity stage</th>
</tr>
</thead>
</table>
| Final fruit retention numbers are presented in Table 3. This shows that mean final fruit retention number per plant was a maximum (453.3) for drip irrigation at 20 kPa soil moisture tension with a mulching treatment. This is 272% higher than the minimum value of 122 fruits per plant for the surface irrigated treatment. However, for fruit retention at marble and maturity stages the interaction between irrigation level and mulching was not significant. The higher fruit retention in the plot irrigated at 20-kPa soil matric tension may be due to the better soil moisture regime and consequently no moisture stress during flowering and fruit development stages. Mulch also maintains an optimum soil temperature and better microenvironment in the plant root zone, besides preventing weeds. This gives better use of nutrients to improve the quality and quantity of the fruits.
**Table 3. Effect of irrigation at different soil matric tensions on final fruit set of mango**

<table>
<thead>
<tr>
<th>Irrigation Treatments</th>
<th>Average fruit set/plant</th>
<th>% Increase over Control (SI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DI₁</td>
<td>363.3</td>
<td>198</td>
</tr>
<tr>
<td>DI₂</td>
<td>321.7</td>
<td>164</td>
</tr>
<tr>
<td>DI₃</td>
<td>220.0</td>
<td>80</td>
</tr>
<tr>
<td>SI₄</td>
<td>122.0</td>
<td>-</td>
</tr>
<tr>
<td>DIM₅</td>
<td>453.3</td>
<td>272</td>
</tr>
<tr>
<td>DIM₆</td>
<td>438.3</td>
<td>260</td>
</tr>
<tr>
<td>DIM₇</td>
<td>436.7</td>
<td>258</td>
</tr>
<tr>
<td>SIM₈</td>
<td>196.7</td>
<td>61</td>
</tr>
</tbody>
</table>

**Fruit yield:** Effect of irrigation at three soil matric tensions on fruit yield of mango was dependent on mulch (Table 4). Increase in fruit yield was highest for mango plots with frequent drip irrigation coupled with mulching. Mango plants irrigated under surface method of irrigation without mulch had lowest yield. Table 4 shows that irrigation and mulching treatments have significant effects on fruit yield. However, the interaction between irrigation and mulching was not significant. The highest fruit yield (76.3 kg per plant) was recorded for plants irrigated at 20 kPa soil matric tension through drip irrigation with plastic mulch as against 18.7 kg per plant for surface irrigation without mulch treatment. The highest yield with drip irrigation and mulching treatments may be attributed mainly to higher fruit retention coupled with production of larger and heavier fruits.

**3.2 Water requirements and water saving**

Amounts of water used in different irrigation treatments are shown in Table 5. No irrigation was applied during June to September 2001 due to sufficient rainfall during this period. Irrigation withheld during November and December to provide a level of stress judged advantageous during flower bud development (Cull, 1989; Larsen and Schafer, 1989; Galan Sauco, 1990; and Mostert and Hoffman, 1997) and to induce flowering.

The quantities of daily water applied ranged from 8 to 64 litres per plant per day for water application at 20-kPa soil matric tension. The maximum daily water application was recorded in May, due to high evapotranspiration from the plants. Amounts of water applied in February, March, April and May varied from 180 to 1544, 135 to 1180 and 90 to 800 litre per plant in the treatments irrigated at 20, 30 and 60 kPa soil matric tension, respectively. In contrast, water applied in surface irrigation treatments was 600, 1150 and 1810 litres per plant, respectively, in the months of March, April and May. Total volumes of water applied were 3150, 2472, 1615 and 3560 litres per plant, respectively, for the 20, 30 and 60 kPa irrigation levels and in surface irrigation treatments during the three months of fruit development of mango. Water saving by drip irrigation at 20, 30 and 60 kPa soil matric tension was found to be 11.5, 30.6 and 54.6%, respectively, compared with the surface irrigated treatments.

**Table 4. Effect of irrigation at different soil matric tensions on fruit yield of mango**

<table>
<thead>
<tr>
<th>Irrigation Treatments</th>
<th>Average fruit yield, kg/plant</th>
<th>% Increase over Control (SI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DI₁</td>
<td>61.0</td>
<td>227</td>
</tr>
<tr>
<td>DI₂</td>
<td>54.0</td>
<td>189</td>
</tr>
<tr>
<td>DI₃</td>
<td>34.7</td>
<td>86</td>
</tr>
<tr>
<td>SI₄</td>
<td>18.7</td>
<td>-</td>
</tr>
<tr>
<td>DIM₅</td>
<td>76.3</td>
<td>309</td>
</tr>
<tr>
<td>DIM₆</td>
<td>73.3</td>
<td>293</td>
</tr>
<tr>
<td>DIM₇</td>
<td>68.3</td>
<td>266</td>
</tr>
<tr>
<td>SIM₈</td>
<td>33.7</td>
<td>80</td>
</tr>
</tbody>
</table>

**Table 5. Mango water requirements at different soil tensions under drip and water savings compared with surface irrigation**

<table>
<thead>
<tr>
<th>Season</th>
<th>Rain, mm</th>
<th>Drip irrigation, litre/plant</th>
<th>Surface irrigation, litre/plant</th>
<th>Water savings, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001-02</td>
<td>1464</td>
<td>456</td>
<td>600</td>
<td>50% AWD</td>
</tr>
</tbody>
</table>

**3.3 Water use efficiency**

Table 6 shows water use efficiency (WUE) for the various irrigation and mulching treatments calculated using fruit yield and water application data. The table shows that the highest water use efficiency of 0.874 kg/m² was obtained for the plot irrigated at 60 kPa soil tension under drip irrigation and mulched conditions. Against this, the lowest WUE (0.162 kg/m²) was obtained for the control plot irrigated by surface irrigation at 50% soil moisture depletion. The WUE at 20 and 30 kPa irrigation levels was found to be more or less same in both mulched and non-mulched conditions. However, WUE was lower at 60-kPa soil matric tension under non-mulched conditions.
as compared with mulching for the same level of irrigation. WUE values were also noted to be higher in all mulched treatments by comparison with non-mulched conditions. This shows that mulching, method of irrigation and level of irrigation have significant effects on WUE. The higher water use efficiency for drip irrigation with mulching is mainly due to the greater fruit yield and lower water use.

Table 6. Water use efficiency of mango in different irrigation treatments

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Water use efficiency, kg/ha-mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>DI₁</td>
<td>5.681</td>
</tr>
<tr>
<td>DI₂</td>
<td>5.716</td>
</tr>
<tr>
<td>DI₃</td>
<td>4.437</td>
</tr>
<tr>
<td>SI₄</td>
<td>1.621</td>
</tr>
<tr>
<td>DIM₅</td>
<td>7.108</td>
</tr>
<tr>
<td>DIM₆</td>
<td>7.762</td>
</tr>
<tr>
<td>DIM₇</td>
<td>8.745</td>
</tr>
<tr>
<td>SIM₈</td>
<td>2.923</td>
</tr>
</tbody>
</table>

4 Conclusions

The following conclusions were drawn from the study:

(1) Final fruits set numbers were higher, at 453, 438 and 437 fruit per plant, for drip irrigated and mulched plots maintained below 20, 30 and 60 kPa soil matric tension as compared with 363, 322 and 220 fruit per plant from the same level of irrigation but without mulch.

(2) The average fruit yield of mango crop was 76.3 kg per plant drip irrigation at 20 kPa soil matric tension with mulch as against 18.7 kg per plant from the surface irrigated plot under without mulch. Water requirements were 3150, 2472, 1615 and 3560 litre/plant in plots irrigated at 20, 30 and 60 kPa soil moisture tension under drip irrigation and surface irrigated plots, respectively, during the three month reproductive growth cycle of mango.

(3) The water saving for drip irrigation at 20, 30 and 60 kPa of soil matric tension was estimated to be 11.5, 13.6 and 54.6%, respectively compared with the surface irrigation treatment.

Acknowledgements

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References


Improving irrigation efficiency: a water pricing perspective

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Abstract
China faces many water resources and environmental problems caused by low irrigation efficiency. The problem is analyzed from the point of view of agricultural water pricing policy. Existing problems in the Chinese agricultural water pricing system are analyzed together with an outline of objectives to be pursued by an agricultural water pricing reform policy. These comprise economic, financial, social, political, and resource and environmental aspects. Two constraints to pricing policy reform are also discussed, namely the current Chinese water resources management system and farmer’s low income. Finally, the Australian experience in water management reform, market-based instruments for water pricing and water trading is presented and lessons from the water reform process are discussed for their relevance to Chinese water resource policy.

Key words: Irrigation, water pricing, China, Australia.

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1 Water pricing problems in Chinese irrigated agriculture

1.1 Introduction
Low irrigation efficiency in China has given rise to concerns in recent decades. It is estimated that water losses in irrigated agriculture, both in distribution systems and cropland, reach 60% of total water diversions (http://www.usembassy-china.org). Average output of per m³ irrigation water is only 1 kg/m³ (Wang et al., 2001), being only two thirds of average irrigation water use efficiencies around the world. Furthermore, a comparable investment in improving water use efficiency in agriculture would yield more water than that of the north/south diversion, which will be expensive and require significant resettlement. (http://www.earth-policy.org.). Besides large water losses, low irrigation efficiency has caused serious environmental and resources problems such as secondary salinization, pollution of groundwater and rivers, over-pumping of aquifers, drying-up of rivers and lakes, and loss of top soil (Gu, 1998, Wang, 1998, Chen, 2000, Zhang et al., 2000). Three-quarters of irrigation land has been salinised in the Yellow River Valley (Phillip Z.K. et al., 1999).

Many technological solutions have been proposed to improve irrigation efficiency, however, these have not provided satisfactory results. In recent literature, water pricing is widely accepted as one of the most effective instruments to solve this problem. Successful experiences in Australia, Brazil and other countries further demonstrate its effectiveness. This paper first analyses current problems of Chinese agricultural water pricing, then puts forward a set of objectives to be achieved by agricultural water pricing reform in China. Finally it analyses some comparative experience of Australian water pricing reform.

1.2 Low water price and low water fee collection rate
Table 1 gives agricultural water price of each province in 1997 (Wei, 2001). In most of provinces water supply for agriculture is almost free of charge, and in nearly one third of provinces water fee is deducted from the state grain levy. Table 2 (Du, 2000) compares national water supply costs and prices during 1988-1998. Water pricing only accounts for 50%-60% of the supply cost. While there is an upward trend in water pricing, it is only maintaining the same proportion of water supply costs. Furthermore, Liu, (1999) shows that cost of agricultural water use only represents 1/8 to 1/5 of profits derived from water supply, 1/20 of output value per ha, and 1/10 of total cost per ha. The national-level agricultural surveys reveal that irrigation and drainage fees for six types of crops per ha is only 5% of material cost per ha, 3% of all cost per ha. In contrast, fertilizer expenditure makes up 35% and 20% respectively (Shen et al., 2000). So agricultural expenditure on water is not commensurate with its value as an input to agricultural production.
Table 1. Agricultural water price in provinces of China in 1997

<table>
<thead>
<tr>
<th>Province</th>
<th>Water Price (Yuan/m³)</th>
<th>Province</th>
<th>Water Price (Yuan/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beijing</td>
<td>0.02</td>
<td>Hubei</td>
<td>0.04*</td>
</tr>
<tr>
<td>Tianjin</td>
<td>0.04</td>
<td>Hunan</td>
<td>0.032*</td>
</tr>
<tr>
<td>Hebei</td>
<td>0.075</td>
<td>Guangdong</td>
<td>0.01</td>
</tr>
<tr>
<td>Shanxi</td>
<td>0.062</td>
<td>Guangxi</td>
<td>0.03*</td>
</tr>
<tr>
<td>Neimenggu</td>
<td>0.023</td>
<td>Hainan</td>
<td>0.017*</td>
</tr>
<tr>
<td>Liaoning</td>
<td>0.03</td>
<td>Sichuan</td>
<td>0.031</td>
</tr>
<tr>
<td>Jilin</td>
<td>0.03</td>
<td>Guizhou</td>
<td>0.02*</td>
</tr>
<tr>
<td>Heilongjiang</td>
<td>0.024</td>
<td>Yunnan</td>
<td>0.02</td>
</tr>
<tr>
<td>Shanghai</td>
<td>0.015</td>
<td>Xizhang</td>
<td></td>
</tr>
<tr>
<td>Jiangsu</td>
<td>0.01</td>
<td>Shaanxi</td>
<td>0.039</td>
</tr>
<tr>
<td>Zhejiang</td>
<td>0.015*</td>
<td>Gansu</td>
<td>0.03</td>
</tr>
<tr>
<td>Anhui</td>
<td>0.042*</td>
<td>Qinghai</td>
<td>0.04*</td>
</tr>
<tr>
<td>Fujian</td>
<td>0.035*</td>
<td>Ningxia</td>
<td>0.006</td>
</tr>
<tr>
<td>Jiangxi</td>
<td>0.016*</td>
<td>Xinjiang</td>
<td>0.18</td>
</tr>
<tr>
<td>Shandong</td>
<td>0.032</td>
<td>Chongqing</td>
<td>0.03</td>
</tr>
<tr>
<td>Henan</td>
<td>0.04</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: * is the water price discounted from the grain levy; Space is no data available.

Table 2. Comparison between water price and water supply cost (Yuan/m³)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Water price</td>
<td>0.008</td>
<td>0.016</td>
<td>0.03</td>
<td>0.06</td>
</tr>
<tr>
<td>Supply cost</td>
<td>0.013</td>
<td>0.029</td>
<td>0.06</td>
<td></td>
</tr>
</tbody>
</table>

Rate of collection of water fees is estimated at only about 50% on average for the whole nation (Lai, 2000). Considering level of cost recovery and fee collection, actual revenues account for less than 30% of water supply cost. A recent study by Wang (2001) verified that on average revenues from water fees account for 38.7% of water supply cost. This situation clearly precludes sustainable operation of water supply infrastructure and companies in China.

1.3 Ill-defined water supply costs and inefficient expenditure

Within multi-function water management units, a number of inconsistencies are apparent in irrational cost allocation between different water uses for irrigation, hydro-generation, and transportation and flood control. Calculation of water supply cost is usually incomplete. Typically, the labor input of farmers for construction of water projects is not included in calculations. For example, during construction of the Miyun and Guangting reservoirs in Beijing, government’s investment in these two reservoirs was 0.94 billion Yuan, and estimated investment as farmer labor was 0.205 billion Yuan (Sun, 2001). Yet this contribution is not considered in calculation of water supply cost. Up to now, use of local farmers’ labor has been very common in construction of water projects (Jiang, 2001). A survey shows that the value of farmers’ labor inputs into water projects, at and below branch canal level, accounts for up to 50-60% of total investment (Zhang, 1996). An obvious gap exists between water supply cost either inclusive or exclusive of farmer input. Also, no defined policy exists for repayments of loans and interests (Liu et al., 1997); nor is there a standard for water resource fees or drainage fees (Zhang, 1997). Another complication is that besides water prices there are fees for enhanced infrastructure, for waterworks construction and fines for excess water use (Hu, 2000).

Water fee revenues are still regarded as a source of general revenues in many provinces rather than operational revenues for water management units, which lie outside the government’s general revenues (Gao et al., 2000). Hence revenues are collected and expended as part of the general government budget. So funds are only partly used for irrigation districts. Table 3 gives income and expenditure details for water fees in a certain city of Shandong Province (Shandong Provincial Water Price Survey Group, 2000a). Only about 60% of water revenues are used for expenditure in irrigation districts.

This problem is also reflected in allocation of agricultural water revenue between different levels of water management units. Statistics for Shaoshan Irrigation District show that agricultural water fee revenues returned to the irrigation district management agency are only 4.8% of total

Table 3. Income and expenditure related to water fees in certain city of Shandong province

<table>
<thead>
<tr>
<th>Since 1998</th>
<th>Water revenue</th>
<th>Proportion allocated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>Yuan/m³</td>
<td>%</td>
</tr>
<tr>
<td>Total water revenue in irrigation district</td>
<td>0.056</td>
<td>100</td>
</tr>
<tr>
<td>Service charge for water fee collection</td>
<td>0.001</td>
<td>1.8</td>
</tr>
<tr>
<td>Fiscal expenditure in city</td>
<td>0.0056</td>
<td>10.0</td>
</tr>
<tr>
<td>Depreciation fund in city level</td>
<td>0.0044</td>
<td>7.9</td>
</tr>
<tr>
<td>Overhaul fund in city level</td>
<td>0.0044</td>
<td>7.9</td>
</tr>
<tr>
<td>Repayment fund for loan in city level</td>
<td>0.0056</td>
<td>10.0</td>
</tr>
<tr>
<td>Expenditure for irrigation district in city level</td>
<td>0.0176</td>
<td>31.2</td>
</tr>
<tr>
<td>Expenditure for irrigation district in county and township level</td>
<td>0.0176</td>
<td>31.2</td>
</tr>
</tbody>
</table>
agricultural water fee. While the original value of fixed assets in main canals is 1.3 times higher than that in branch canals, money spent on maintenance and repair of branch canals is 4.1 times that of the main canal (Zhang et al., 1999). In a provincial survey, the agricultural water price only meets 22% of water supply costs, of which 30-50% is used for operation of irrigation districts (Hui, 2001).

1.4 Inadequate pricing structure and weak monitoring system

In China, water prices are independent of irrigated crops or water sources. Existing pricing structures take into account use of water for industry, agriculture and urban life (Liu, 2000) but do not differentiate between surface water, groundwater, diverted water or treated wastewater (Tan, 1999, Shen et al., 2000). Finally, water price also often does not change over time. For example, the current water price was formulated over ten years ago at the head of a diversion canal on the Yellow River (Shandong Provincal Water Price Survey Group, 2000b). During this period, economic development, available water resources and industrial policy in Shandong Province have undergone great changes. It is not difficult to imagine that such a pricing system may lead to problems. An unreasonable ratio may also exist between bulk and retail prices. The Bishihang irrigation district supplies raw water for treatment at only 0.05 Yuan/m³ while end water users must pay 0.73 Yuan/m³, the ratio of the former to the latter is 7%. However, generally 30% is common in China.

Water pricing is still controlled by government policy or administrative orders. There is neither water users’ participation nor a strict monitoring or regulatory system. Such a pricing system will not have equality of access to information by participants, nor will it take account of the will of water users; thus it is very difficult to implement in practice. Regulations covering water price formulation in China were issued in 1985, and are described in Table 4 (Wei, 2001). Comparing Table 4 with Table 2, clearly a large gap exists between national regulations and actual water prices.

2 Objectives of Chinese agricultural water price reform

2.1 Introduction

Faced with very low irrigation efficiency, large water losses, increasing water shortage, worsening environment and long-term financial deficits of water supply companies, Chinese agricultural water pricing reform is urgently needed. Its objectives should be multi-purpose, considering the financial viability of water supply companies, users’ acceptability, environmental sustainability, and irrigation water use efficiency.

<table>
<thead>
<tr>
<th>Classification of water use</th>
<th>Standard of water price use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain crops</td>
<td>Water supply cost</td>
</tr>
<tr>
<td>Cash crops</td>
<td>Slightly higher than water supply cost</td>
</tr>
<tr>
<td>Industry</td>
<td>Water supply cost+4-6% of water supply investment</td>
</tr>
<tr>
<td>Urban life</td>
<td>Water supply cost +slight profit</td>
</tr>
<tr>
<td>Hydro-generation</td>
<td>8% of electricity price income</td>
</tr>
</tbody>
</table>

Table 4: Current regulation on water price formulation of China

2.2 Financial objective: self-sufficiency

Physical and institutional sustainability of water supply services is a basic requirement of any water pricing system (Mahmond, 2001). However, the water fee revenues in China cannot ensure such an operation. Actually, water supply companies have found it very difficult to continue operation in the present situation, if the subsidy from the government is fully removed (Wei, 2001). So self-sufficiency is a key objective in reforming Chinese water resource management.

2.3 Economic objective: efficiency

Water use efficiency must be another key objective of water pricing reform as misuse and overuse of irrigation water has been common, causing many environmental problems. In the short run, it is impossible to realize a primary objective of water pricing equaling marginal cost. This remains necessary to balance supply and demand through a pricing mechanism. But, a secondary objective should be established to promote water use saving, namely making the user aware of an incremental charge related to incremental use. Water markets should be contemplated in the longer term as water resource management institutions and legal frameworks become established and more developed.

2.4 Social objective: social equity and users’ affordability

Social equity means that users should be charged according to their ability to pay (Karen, 2001). This is an important consideration in Chinese irrigated agriculture. According to a survey (Jiang, 2001), annual net income per ha of grain crops was 4500-6000 Yuan in 1999, which does not include the farmers’ labor inputs. If labor input were calculated according to a real worker’s salary, the farmer’s budget would be in deficit.
Under these circumstances, it is not possible to increase agricultural water prices greatly. It is obvious that water reform must be accompanied by an overall agricultural policy, which enables farmers to diversify their crops, and improve incomes.

2.5 Political objective: political acceptability and practical feasibility

While a water pricing policy may be feasible to implement in all other aspects, it will be doomed to failure if it is not politically acceptable. Food security is of paramount importance in China. About 70% of grain output in China originates from irrigated land, especially in the North and West of China where there would be no agriculture without irrigation. If water price is much higher than the farmers’ ability to pay, then farmers would be forced to give up irrigation. This would not only affect national food security but also social stability, since many employment opportunities would be lost. Proposed actions must also be feasible in practice. Now, volumetric pricing is impossible to implement in the short term because of high cost and lack of flow measuring infrastructure. Future rehabilitation and modernization of irrigation projects should consider equipping those systems with adequate flow measuring devices.

2.6 Environmental objective: environmental sustainability and resource reuse

The existing water pricing policy does not consider the value of water itself, or any environmental externality caused by its use. This has caused severe environmental sustainability problems. An environment monitoring report for 1997 claims that over half of the river sections of seven main rivers and 17 out of 35 key lakes in China have been seriously polluted. The Yellow River had zero flow at the mouth for 226 days in 1997, while the Hai River has become a seasonal river and the regional ground water depression area has increased to 158,000 km² due to overuse. The area of soil and water erosion in China has increased to 3,670,000 km², or 38% of the whole territory area. N, P and K fertilizer amounts flushed in the loess plateau are estimated at 40 million tons annually, which is equivalent to the annual fertilizer output in China (Zhang et al., 2000). Thus environmental protection has become an increasingly significant issue in China.

As usually occurs in water policy, possible conflicts arise among these objectives. The most typical contradiction is efficiency and equity, while others include public acceptability and financial sufficiency. Sometimes issues concern economic efficiency and political acceptability or financial sufficiency and ease of implementation. Compromises are necessary to find the middle ground in relation to the present situation of China, especially when some objectives are emphasized, such as irrigation water use efficiency.

3 Potential problems with Chinese water price reform

3.1 Introduction

In most developing countries, the agricultural sector is politically sensitive and sometimes even dominant. Thus charging users for water and irrigation water services is also a sensitive issue, which involves political, historical, social, religious and economic dimensions (Mahmoud, 2001). In China, many difficulties will have to be faced when water price reform is carried out.

3.2 Water resources management system

In China, water resources belong to the state, with every level of government being an agent of state control over local resources. Generally speaking, national level authorities take precedence over local levels. In water resource administration, agricultural irrigation, aquaculture, electricity, urban water supply and transportation are the responsibility of parallel departments at the same level, having the same rights in construction and management of surface water. Large river basins, such as the Yangtze, Yellow, Hai and Zhujiang Rivers, have their own river management Commissions to coordinate each river catchment (Xiong et al., 1998).

Such an administrative system creates many difficulties in introducing water pricing reform. Firstly, such a system ignores natural laws of water resources, being in-appropriate for integrated catchment management. This has caused inconsistent water pricing between upstream and downstream users, between surface and groundwater in the same region, while pricing does not include waste treatment costs, as diversions and drainage are managed by different departments. Secondly, the vertical administrative structure is excessively long, weakening the government monitoring function and blurring water rights. Too many departments are involved in management and construction of river works with many agencies having the right to disposal of effluents. Thirdly, in such a system there is no a clear division between government, the water supply company and the private user. Both the water management department and Water Supply Company have dual roles of operation and monitoring, creating conflicts of interest due to lack of definition of their roles. The fact that state-owned assets are lost, water projects are aging, or out of repair for many years, shows the government’s deficiency in this regard (Shen, 2000).

Administrative expenditure in some water management units accounts for one third of total
cost of operation. Staff salaries in urban water supply companies are higher than the average for urban centres according to a sample survey of water prices in key cities (Liang, 2000). Many water supply companies put more emphasis on increasing government subsidies rather than balancing the budget by increasing water fees or improving efficiency through cost savings (Gao et al., 2000). Deficiencies in Water Company’s operation directly affect water supply costs and water pricing. Under such a system, water is priced by administrative orders rather than reflecting actual costs of supply and/or the value of water. Since Chinese reforms and the economic opening-up policy have been in place for over twenty years, a market economy is now established, the market has become the main instrument to allocate economic resources. As water is a basic resource closely linked with all industrial sectors of national production and people’s life, so administrative pricing not only distorts water demand and supply, but also the allocation of other economic resources.

In summary, unlike other resources, water is managed separately according to administrative regions, water property rights are weak and ill-defined, water is priced by administrative orders and water supply operation and monitoring functions are poorly delineated. All of these factors make the reform of agricultural water pricing very challenging.

3.3 National agricultural policy

Farmers’ incomes have shown a decreasing trend in China over recent years. According to a survey on agricultural material costs in Shandong Province in 1999, grain revenue has significantly decreased for three years in a row, leaving little left after agricultural tax is levied. Average net benefit per mu in 1999 is 66.43 Yuan, was only 23.2% of that in 1996 when agricultural income was the highest (Shandong Provincial Water Survey Group, 2000b). In fact, an unfavorable balance between agriculture and industrial development has existed in China since 1949, and the gap has increased further in recent years. Low-income farmers are not a new phenomenon in China, but the severity of the problem has accelerated in recent years. Changes in agriculture policy as a result of China’s joining the WTO could potentially aggravate the problem in future years. So in the short run, concern over social equity in agricultural water pricing greatly hinders realization of other water reform objectives.

4 Experiences from Australian water reform

4.1 Water resources development

Australia is the driest continent on earth and water availability is subject to a high level of variability. These conditions make management of water resources more challenging to achieve the goal of sustainable development. The Murray-Darling Basin is the most important water resource system in Australia. It occupies 14% of the country’s area and accounts for 75% of the 2.4 million ha of irrigated land. Water resources development in the basin commenced at the turn of the 20th Century and continued until the late 70s. At this time a marked shift in emphasis took place, from growth in water resource allocation and use, towards management. This change in emphasis was due to environmental impacts resulting from over allocation of the resource, which manifested itself in the form of increased soil salinity and deterioration of water quality. In 1994 the Murray-Darling Basin Commission, charged with managing the basin soil and water resources, decided to cap diversion of surface water at the level of infrastructure development then reached.

4.2 Water resources reform

Management of water resources in Australia is the responsibility of State Governments. As such, it is common that development and management objectives may differ between governments. In 1995, the Council of Australian Governments (COAG) State Governments agreed to implementation of a comprehensive reform agenda aimed at putting water resources management on a sustainable footing. This reform package in the water sector forms part of a comprehensive competition policy across all sectors of the economy instituted in the early 90s. COAG identified several major aspects that required changes in the water sector (Pigram et al., 1994) including:

- Pricing reforms, including full cost recovery, removal of cross-subsidies and asset refurbishment;
- Institutional and organizational reforms;
- Clarification of property rights to water, and adoption of trading arrangements;
- Allocation of water to the environment; and
- Community consultation and knowledge enhancement programs.

One of the key outcomes of the COAG reform agenda is related to water allocation, property rights and water trading. Separation of water allocations from land ownership and reservation of environmental flow allocation forms the basis of these reforms. Critically, water trading is predicated as the key mechanism to ensure that water is used for the highest productive use. A key element to achieve an efficient water market is the capping of resource allocation (Figure 1). It is not

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1 The COAG comprises the Governments of the 6 States and the Federal Government of Australia.
possible to institute water trading if new resources continue to be allocated at non-market price.

Figure 1. Cap on water diversions in the Murray-Darling Basin.

Whilst water trading in the Murray-Darling basin commenced in the early 90s, a significant increase in the volume of trading occurred after 1994. Figure 2 shows volumes of water traded in the state of Victoria over the past decade. There are two main forms of water trading: temporary trade where the use of the resource is ceded for one year, and permanent trade where the use of the resource is ceded in perpetuity.

4.3 Water Pricing

4.3.1 Service Price

One important principle of the COAG reform agenda is provision of irrigation and drainage service on a full cost-recovery basis. The COAG Communiqué (Greig, J, 1998) of 1995 states that, for commercial water functions such as urban water supply and rural water supply, "where charges do not currently fully recover the costs of supplying water to users, charges and costs must be progressively reviewed so that no later than 2001 they comply with the principle of full cost recovery”. COAG also defined costs in terms of economic costs and accounting costs as shown in Figure 3. Economic costs include all costs of water management including the externalities such as salinity and other environmental impacts, while accounting cost only include finance, depreciation and administrative costs. Implementation of the COAG principles across the country led in most states to separation of the resource management function and commercial function of supplying water to urban and rural customers.

As a result of the COAG reform process, price of water services has steadily increased in most irrigation districts to reflect the need for full recovery of service costs by the providers, as government subsidies were phased out. Table 5 shows the cost recovery ratio for several irrigation systems in Australia. Here, cost recovery ratio is defined as the ratio of gross revenue to total costs excluding capital expenditure and depreciation. Most authorities are now recovering all the operation and maintenance costs and in some cases up to 50% of the capital investment cost. Ratios vary from 0.51 at G-MW Woorinen to 1.63 in South West (Western Australia).

4.3.2 Water Trading

As indicated above, trading of water entitlements both on a temporary and permanent basis has increased substantially as a result of implementing COAG reforms. The price of water on the trading market reflects what users are prepared to pay to obtain additional water to meet the needs of their farming enterprises. Water prices across the country vary widely as a result of several factors that operate in the market such as weather conditions and commodity prices. In economic terms, the price that farmers are prepared to pay for each additional volume of water purchased reflects the marginal price of water. Water has been traded on the temporary

Figure 2. Annual volume of permanent and temporary water trading in Victoria Australia

Figure 3. Economic and accounting cost criteria
market for up to $450/ML while on the permanent trading market water has been traded to up to $1200/ML. These prices are a reflection of the true value of water.

Table 5. Cost recovery ratios and service charge for several Australian systems.

<table>
<thead>
<tr>
<th>System</th>
<th>Cost Recover Ratio</th>
<th>Service charge ($/ML)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coleambally NSW</td>
<td>1.28</td>
<td>13.80</td>
</tr>
<tr>
<td>Jemalong (NSW)</td>
<td>1.21</td>
<td>20.71</td>
</tr>
<tr>
<td>Murray Irrigation (NSW)</td>
<td>1.15</td>
<td>8.18</td>
</tr>
<tr>
<td>Central Irrigation (SA)</td>
<td>1.50</td>
<td>34.00</td>
</tr>
<tr>
<td>G_MW Murray Valley (VIC)</td>
<td>1.03</td>
<td>19.35</td>
</tr>
<tr>
<td>G-MW Shepparton (VIC)</td>
<td>0.83</td>
<td>24.02</td>
</tr>
<tr>
<td>G-MW Central Goulburn (VIC)</td>
<td>0.81</td>
<td>24.39</td>
</tr>
<tr>
<td>G-MW – Woorinen</td>
<td>0.51</td>
<td>28.10</td>
</tr>
<tr>
<td>G-MW Rochester</td>
<td>0.82</td>
<td>20.75</td>
</tr>
<tr>
<td>South West (WA)</td>
<td>1.63</td>
<td>37.05</td>
</tr>
</tbody>
</table>

1 ML = Megalitre: Volume of 1000 m³

Statistics show that traded water is moving towards production of higher value crops with higher returns to growers. A large volume of water trade in the State of Victoria originates from low productivity farming primarily devoted to production of lamb and wool with relatively low return on water (A$30-A$50/ML). It has been shown that much of this post-trade water is used for production of high value horticulture crops such as vineyards and fruit trees with returns on water in excess of A$1,000/ML.

There is a marked difference between the price of water in the trading market and the water delivery charges imposed by most service providers, shown in Table 5. This is the best indication that the price of service delivery would have to increase several folds before it is likely to have an impact on the productivity of water.

Whilst there is sufficient evidence to corroborate an increase in the economic productivity of water, there is a paucity of data on the impact of water trading on biophysical efficiency of irrigation. Recent surveys show that most water buyers are equipped with pressurized irrigation systems. These systems are likely to deliver higher application efficiency than the flood irrigation used on pastures by wool and beef growers. This is an area that requires further research to quantify potential gains arising from water trading.

Thus far, water trading has been largely confined to the agriculture sector. However, the COAG agenda aims to eliminate any constraint on inter-sectoral trading in the long term. Such an extension in trading will most likely increase the market price of water as urban suppliers and users may be prepared to pay a higher price for water.

Whilst water reform processes must be designed with specific reference to the economic, legal and political framework of each country, several general aspects of the Australian water reform process may provide useful lessons for Chinese agricultural water pricing policy:

? Water pricing reform must be based on adequate water management information systems, institutions and infrastructure. A prerequisite for successful water reform is well-defined and applied water property rights, integrated management of water resources, especially management of surface water and groundwater as “one-resource.”

? Government must play a key role in defining and enforcing water allocation to consumptive and environmental uses.

? Water service costs must be clearly delineated to define water-pricing policies. If full cost recovery is the preferred policy option, it should be implemented progressively and with full transparency of actual service cost.

? A combination of water service pricing and water trading has the potential to drive water use towards high revenue crops and more efficient irrigation system. Water markets can better reflect the marginal price of water and provide greater incentives to improve water use efficiency and water productivity.

5 Conclusions

Rationally priced water has been increasingly regarded as an effective solution to improve irrigation water use efficiency. Existing problems in Chinese agricultural water pricing include low price and fee collection rate, undefined components of supply cost, irrational expenditure of fee revenues, poor price structure and weak monitoring system causing low irrigation use efficiency, long-term debt of water supply companies, and a number of environmental and resource problems. So, the objective of Chinese agricultural water pricing should be comprehensive, with financial, economic, social, political, resource and environmental objectives being considered concurrently. When agricultural water price reform is carried out, two real problems must be faced, being the irrational water resource management and farmers’ low income.

Australia has embarked on a program of water reform for the last decade, which has led to an increase in transparency in the price of water supply services and a very active water market. This process is based on a set of principles set by COAG to ensure transparency in provision of water services and environmental sustainability. Price of water supply has steadily increased to meet the requirement of full cost recovery by
water service providers.

A very active water market has enabled increased productivity of water in agriculture. Large amounts of water are transferred from low to high productivity crops increasing the return on water from as low as A$50 to as high as A$1200. To date, insufficient data is available to quantify potential gains in bio-physical efficiency, although recent surveys show that water buyers are using better irrigation technology to apply water on their farms.

The current reality of Chinese agricultural water pricing and the Australian water reform experience suggest that water price reform in China should be carried out in a combined institutional and legal reform. These are prerequisites for establishing market-based mechanisms to promote higher water use efficiency and productivity, while taking resource and environmental protection into consideration.

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Engineering innovations to improve irrigation efficiency

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Abstract
Two examples are given of engineering innovations to improve water use efficiency in irrigation. Firstly, water savings are possible for light soils by converting from surface to overhead irrigation practice but the related energy supply needs to be affordable and sustainable. Use of combined wind and solar cell units to power sprinkler or drip systems was examined with two types of pump powered by direct current (DC). A wetted diameter of 1.1-2.6 m was possible with the 60 W submersible pump. Tests showed that a 120 W diaphragm pump was capable of producing a 10 l/minute flow with a pressure of 10 m water head. Pumps drew supplies from tanks containing artificial zeolites for water clarification by coagulation. Both arrangements seemed compatible with energy storage using a conventional car battery. Secondly, successful hydraulic regulation of irrigation control gates has considerable benefits. A new means of achieving this uses a regulation plate that is rigidly connected to a float, which is actuated by water levels upstream of a weir in the supply channel. Movement of the regulation plate promotes a steady offtake flow despite large variation in upstream water levels. Corresponding improvements to water distribution efficiency are described for Japanese irrigation networks.

Key words: Natural energy, micro irrigation, car battery, water diversion, buoyancy

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1 Introduction
With the rapid increase of population, expecting an advanced life style, water shortage has become a serious problem in the world and water allocation for agriculture is decreasing steadily. Attainment of stable supplies and effective use of water resources has become more important, so innovations are needed to increase the efficiency of using available water. This means achieving highly efficient water management, water saving through micro irrigation, securing new water resources, developing convenient water treatment and making modifications to reduce leakage and maintain water levels in long canals.

2 Sprinkler and micro irrigation with natural energy
2.1 Power supplies
Renewable energies such as solar and wind power generation can be directly applied to direct current (DC) pumping. An arrangement was tested allowing direct connection to a DC pump, so that power generators running in parallel could recharge the consumed power. For a 28-amp hour battery capacity and discharge to charge ratio of 5-hours, the 60 W (5A) pumps could operate as described in Table 1. The generators included a medium and small sized solar panel rated at 48*4 W and 7.2*6 W, respectively, along with a wind power generator rated at 20 W during maximum power generation. With minimal lift and friction head to overcome, a Shafiro pump (made in USA) can produce 10 l/min for a head of 10m. This small submersible pump is rated at a maximum of 70 l/min when drawing about 5A at 12V (Table 1).

2.2 Micro sprinkler irrigation
Water pumped from the tank was conveyed to a water meter, a control valve, a 10m length of F20 and F13 mm PVC pipe and connected by short vinyl pipe to micro sprinklers. The pump was powered by solar and wind power supply described earlier. The spray radius was 0.55-1.30 m for each of the 4 sprinklers, delivering a maximum of 183.2 l/h as a part of system shown in Figure 1. The site had a high level of solar radiation. Surplus power was produced and, after the experiment, the battery was checked to reveal the conditions described in Table 2.

2.3 Drip irrigation
In the small scale pumping for micro irrigation, a coagulation and/or filtration process is often needed to prevent the clogging of drip tubes and water pipelines. The last sprinkler in Figure 1 was replaced by a 12m length of drip tube, which had 4 emitters on a 0.8m- spacing. The last sprinkler in Figure 1 was replaced by a 12m length of drip tube, which had 4 emitters on a 0.8m- spacing. The last sprinkler in Figure 1 was replaced by a 12m length of drip tube, which had 4 emitters on a 0.8m- spacing. The last sprinkler in Figure 1 was replaced by a 12m length of drip tube, which had 4 emitters on a 0.8m- spacing. The last sprinkler in Figure 1 was replaced by a 12m length of drip tube, which had 4 emitters on a 0.8m- spacing. The last sprinkler in Figure 1 was replaced by a 12m length of drip tube, which had 4 emitters on a 0.8m- spacing. The last sprinkler in Figure 1 was replaced by a 12m length of drip tube, which had 4 emitters on a 0.8m- spacing.
pressure head. Tests lasted 30 and 60 minutes, respectively.

Table 1 Current drawn by submerged pump with water head (max 70 l/min)

<table>
<thead>
<tr>
<th>Head (m)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current (A)</td>
<td>5.5</td>
<td>5.1</td>
<td>4.5</td>
<td>3.7</td>
</tr>
</tbody>
</table>

Table 2 Battery conditions during micro irrigation and charging

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Before pumping</th>
<th>2 hours pumping</th>
<th>4 hours charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>1.29</td>
<td>1.22</td>
<td>1.21</td>
</tr>
<tr>
<td>Voltage</td>
<td>12.3 v</td>
<td>12.0 v</td>
<td>12.5 v</td>
</tr>
</tbody>
</table>

2.4 Results of consumption and charging of battery

After the field test was over, the condition of battery and its recharging were checked. In open circuit, the range of voltage was 14.4-12.5V with specific gravity of each cell in the range 1.28-1.24, showed good condition to use with temperatures of the battery (<45°C). Outside this range, the battery needed recharging. Considering the recharging current for < 0.1 of the 5-hour discharge ratio, a 2.1A supply was measured from the medium-sized solar panel. A compact battery charger with converter from commercial AC power source to DC for this 60 Ah, type 20, battery required to develop 15.6 V. Once the voltage level has recovered, then the specific gravity rises also in recoverable region. But for higher specific gravity with sufficient charge, longer charging was necessary as described in Tables 3 and 4.

2.5 Amelioration of stored rainwater by artificial zeolites

A pond was used to gather rainwater but natural conditions and surrounding trees promoted growth of algae on the surface of the pond in summer. Rainwater only enters through many filters made up of leaves, bushes and trees surrounding this pond and no wastewater enters the pond. It was tested to see if artificial zeolites could be used to purify the water by coagulation to suit the micro irrigation process. Blending of these could be done by pumps. A rapid fall in COD occurred from 50 to 10 mg/l in 10 minutes and degree of transparency changed from 25 to 50 cm. Again the battery pack was recharged by solar and wind power.

Table 3. Battery consumption and 1daylight time charge by solar energy

<table>
<thead>
<tr>
<th>Parameter</th>
<th>60 minutes pumping</th>
<th>1 daytime charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>13.7v</td>
<td>12.6v</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>1.25</td>
<td>1.23</td>
</tr>
</tbody>
</table>

Table 4. Chemical components of artificial zeolite

<table>
<thead>
<tr>
<th>Components</th>
<th>Weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>A $\text{I}_2\text{O}_3$</td>
<td>11.7</td>
</tr>
<tr>
<td>SO$_3$</td>
<td>18.9</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>0.2</td>
</tr>
<tr>
<td>CaO</td>
<td>18.5</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>19.4</td>
</tr>
<tr>
<td>Cl</td>
<td>0.2</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>3.9</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>10.3</td>
</tr>
<tr>
<td>MgO</td>
<td>0.7</td>
</tr>
<tr>
<td>OH</td>
<td>15.4</td>
</tr>
</tbody>
</table>
3 Water control system by automatic diversion with buoyancy effects

3.1 Introduction
In large-scale water management systems, the role of water diversion works is extremely important. An increase in the number of the diversions causes a great deal of instability throughout the entire water management system. This apparatus ensures stable downstream conditions during diversion from open canals with considerable variation in water height.

3.2 Basic Automatic diversion apparatus with buoyancy
The original version is given in Figure 2 with Figure 3 showing a revised version that includes a weir. The diversion water is controlled by a stop plate that is rigidly connected to a float. The buoyancy effect of the flow gauging weir can be calculated. And the ratio of the variation ratio at \( G \) by \( H \) at the output showed 0.03-0.06, without regulation it showed 0.25. Later some improvements were added to function as a shock absorber and act against water hammer effects. Once the orifice was changed to take the form of a weir, then more accurate diversion became possible for a wide range of water depth at intake side of the Meiji Canal System in Aichi Prefecture, Japan. Figure 4 shows the longer semi-closed pipe line with automatic diversion at HANANOKI head works that had only 1% error in diversion accuracy was gained with the wide weir. This water management system contributed to achieving an unbiased water distribution between upstream and down stream parts.

4 Conclusions
Micro irrigation is very important for water saving agriculture but treatment is often required for muddy water, which might make use of artificial zeolites. Here, a renewable energy pump has been shown to operate micro irrigation equipment and a water treatment system. The associated battery can be recharged many times. So it was concluded that small-scale micro
irrigation with renewable energy meets the needs of low cost operation, water saving features and capability to improve water quality by simple treatment. Next, the automatic diversion apparatus showed a means of fair water distribution to downstream users.

Acknowledgements
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Modeling Irrigation for Best Management Practices

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Abstract
An irrigation simulation package, CHAIN\_IR, was developed to simulate field water flow, root uptake, and chemical transport with the nitrification chain reaction: $\text{NH}_4^+ \rightarrow \text{NO}_2^- \rightarrow \text{NO}_3^-$. Computer modeling was conducted to quantify distributions of soil water and nitrogen species, and to study the potential of nitrate leaching to groundwater in flood and drip irrigation fields. To account for variability and uncertainty related to soil hydraulic properties and flow processes, stochastic modeling was conducted to simulated water flow and chemical transport in heterogeneous soils under flood and sprinkler irrigations. Simulation results showed that drip irrigation reduced the amount of water leaching from the root zone more than twice that of flood irrigation. Compared with drip irrigation, flood irrigation resulted in 15 times more NO$_3^-$ leaching from the root zone, which eventually reached groundwater. During high evaporative demand, drip irrigation also provided more efficient root uptake than flood irrigation. Stochastic analysis showed that higher spatial variability results in larger amounts of water and chemical leaching. Compared with flood irrigation, sprinkler irrigation is less affected by soil spatial variability and should be a preferred choice to reduce deep leaching and groundwater contamination for soils with high variability and heterogeneity. This study provides the necessary information for developing and/or improving irrigation management to increase water- and fertilizer-use efficiency and to enhance crop productivity.

Key words: Irrigation; modeling; best management practices; soil heterogeneity.

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1 Introduction
The quality of soils, surface and groundwater supplies is a nation-wide concern for agricultural, health, and environmental reasons. Mismanagement of pesticides and fertilizers has caused serious contamination of groundwater in many locations (Lau and Mink, 1987). The United States Environmental Protection Agency (U.S. EPA, 1990) surveyed 1,300 wells throughout the country for 101 pesticides, 25 pesticide break-down materials and nitrate. Nitrate was the major pollutant in over half the wells sampled. As nitrogen fertilizer and pesticide use in the United States has increased steadily so the amounts of chemicals being transported to groundwater has likewise increased (U.S. Department of Agriculture, 1990).

Proper management of irrigation, pesticides, and fertilizers can increase agricultural productivity and control water quality degradation. Micro-irrigation, such as drip irrigation, provides opportunity for precise applications of water, pesticides and fertilizer. Such irrigation methods are being developed as environmentally-friendly farming practices and systems. Micro-irrigation is rapidly becoming the best irrigation choice for high value crops in California, Washington, and Florida. Acreage of micro-irrigation in other states of the US is also increasing as water costs become higher and degradation of groundwater water quality grows more serious.

Micro-irrigation has many advantages for agriculture and the environment. However, many theoretical and practical problems need further study. For example, how do we quantitatively describe the interrelationships among soil, water, and plant? How do we predict water flow and chemical transport accurately in a multi-dimensional and dynamic system? How do we design an optimal irrigation system in terms of agriculture productivity and water quality?

The high cost of sampling and analyzing pesticide and nitrate concentrations in the field means that there are only a limited number of field experiments are possible to study best management practices (BMPs) in
irrigation systems. Zazueta et al. (1984) developed a microcomputer system for the management of irrigation. Phene et al. (1989) used a weighing lysimeter coupled with a computer to control the application of water and nutrients through a subsurface drip irrigation system. Clark et al. (1991) used tensiometers and fertigation with micro-irrigation to improve water and fertilizer management. However, current technology for computer-controlled irrigation does not integrate potential groundwater contamination into the decision-making processes. Moreover, the sensor technology may not be economically feasible.

Water flow and chemical transport in soils under different irrigation methods are two- or three-dimensional problems. Some analytical and numerical solutions have been developed to solve the flow equations with relatively simple initial and boundary conditions (Bresler, 1975; Warrick, 1985; Omary and Ligon, 1992). However, no available model is adapted to schedule irrigation. LEACHM (Wagenet and Hutson, 1987) is frequently used to simulate nitrogen movement, transformation, plant uptake, and leaching. Unfortunately, reliability of the simulation results by the one-dimensional model is questionable due to the over simplified assumptions to transform a two- or three-dimensional physical problem to a one-dimensional mathematical problem. So, it is necessary to use more comprehensive models during development of best management practices in irrigation systems.

Natural soils are highly variable and heterogeneous (Degroot and Baecher, 1993). Spatial variability of soil properties can affect soil water and chemical movement, storage, and availability, and introduces uncertainty into irrigation management. Leaching processes of water and chemicals are closely related to different irrigation methods and field conditions (Hergert, 1986; Jaynes and Rice, 1993). However, little research has been conducted to study the interactions of irrigation methods and soil variability on water and chemical transport in irrigated soils. Deterministic models to describe chemical transport in homogeneous soils have been well developed (van Genuchten, 1980). Experimental and theoretical studies suggest that deterministic solutions of transport models may not represent field conditions because they do not account for variability and uncertainty related to soil properties. Saturated hydraulic conductivity ($K_s$) is a key soil property that directly controls water movement and chemical transport in soils. Stochastic methods have been applied in characterizing the heterogeneous nature of $K_s$ (Freeze, 1980; Tompsoon et al., 1989). Spatial distributions of saturated hydraulic conductivity have been used to study water infiltration, solute movement under different irrigations, and slope stability in heterogeneous soils (Freeze, 1980; Wang et al., 1997; Gui et al., 2000).

This paper first introduces an irrigation simulation package. Then the computer model is used to study soil water and nitrogen distributions under flood and drip irrigations. The aim is analyzing water and chemicals uptake by roots with amounts leaching out of the root zone. Another objective is to combine variability of saturated hydraulic conductivity into irrigation simulation models to evaluate effects of soil spatial variability on water and chemical transport in heterogeneous soils under flood and sprinkler irrigations.

2 Materials and methods

Soil water flow associated with field irrigation line sources (furrow, flood, and drip irrigations) can be described by the following Richards’ Equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(K \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial z}\left(K \frac{\partial h}{\partial z}\right) - \frac{\partial}{\partial r}\left(r \frac{\partial h}{\partial r}\right) - \frac{\partial}{\partial z}\left(z \frac{\partial h}{\partial z}\right) - S$$

(1)

where $\theta$ is the volumetric water content, $h$ is the pressure head, $z$ is depth, $r$ is a spatial coordinate, $t$ is time, $S$ is the root-uptake term, and $K$ is the unsaturated hydraulic conductivity function. For drip irrigation with a point source, soil water movement can be considered as asymmetric three-dimensional flow in a variably saturated porous medium. The governing equation for these conditions is given by

$$\frac{\partial \theta}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r \frac{\partial h}{\partial r} \right) + \frac{\partial}{\partial z} \left( z \frac{\partial h}{\partial z} \right) - \frac{\partial S}{\partial z}$$

(2)

where $r$ is the radial coordinate. Unsaturated soil hydraulic properties are described by a set of closed-form equations (van Genuchten, 1980):

$$S_e(h) = \frac{\theta_s - \theta}{\theta_s - \theta_n} = \left[1 + \left(\frac{h}{\theta_s - \theta_n}\right)^{\alpha}\right]^{-}\frac{m}{\alpha}$$

(3)

where $m = 1 - 1/n$ ($n > 1$), and

$$K = K_s S_e^{1/2} \left[1 + (1 - S_e^{1/m})^m\right]^{2}$$

(4)

In which $\theta_s$ and $\theta_n$ denote the residual and saturated water contents, respectively, $n$ and $m$ are retention parameters, and $K_s$ is the saturated hydraulic conductivity.

To characterize the three-step nitrification chain
(NH₄⁺, NO₂⁻, NO₃⁻) in an irrigation field, we use the following chemical transport equations:

\[
R \frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} + \frac{\partial c}{\partial x} + D \frac{\partial^2 c}{\partial z^2} + \frac{\partial c}{\partial z} - R c
\]

(5)

\[
R \frac{\partial c_i}{\partial t} = D \frac{\partial^2 c_i}{\partial x^2} + \frac{\partial c_i}{\partial x} + D \frac{\partial^2 c_i}{\partial z^2} + \frac{\partial c_i}{\partial z} - R c_i
\]

(6)

where \(c_i\), \(c_2\) and \(c_3\) are solution concentrations of NH₄⁺, NO₂⁻, and NO₃⁻, respectively. \(\mu\) is a first-order degradation constant, \(D_x\) and \(D_z\) are dispersion coefficients, \(v_x\) and \(v_z\) are average pore water velocities in the \(x\) and \(z\) directions, respectively, and \(R\) is a retardation factor.

The water flow and chemical transport equations are solved using a finite element method. A software package, CHAIN_IR (Zhang, 1995), was developed based on CHAIN_2D by Simunek and van Genuchten (1994), to simulate water flow, root uptake and movement of chemicals during irrigation. CHAIN_IR can model surface and subsurface irrigation, as well as 3-D asymmetric problems, such as drip irrigation with point sources, and 2-D problems, such as drip, furrow and flood irrigations with line sources. The model can be applied to simulate various scenarios of different soils, irrigation schedules, rainfall and evaporation, root uptake, different crops, and chemical transport with chain reactions: NH₄⁺, NO₂⁻, NO₃⁻. Usually solute equations are a simplified form for transport in a homogeneous soil during steady-state water flow. In CHAIN_IR (Zhang, 1995), more sophisticated equations have been implemented so that chemical transport can also be simulated in heterogeneous soils during transient water flow.

Simulation of irrigation systems can be controlled in two ways. The first is to use a soil water pressure head (matric potential) measured by a tensiometer. This simulates an automatically controlled irrigation system. The controlled soil water pressure value and tensiometer location can be specified to model a full irrigation, without plant stress, or partial irrigation. For full irrigation, a relatively low tension close to zero is specified to maintain moist conditions. As the soil water tension at the controlled location rise above the specified tension, the irrigation system will be turned on.

Similarly, a relatively high tension or more negative pressure is used for a stressed irrigation. A reasonable control location can be the "driest possible" point within the root zone. The controlled tension can also be an average of several tensiometer readings within the root zone. The second control method is a timetable prepared by the user. From the timetable, the program reads information on flux or pressure changes with time to specify the conditions for irrigation, rainfall, and evaporation.

To characterize soil spatial variability, the saturated hydraulic conductivity \(K_s\) in Equation (4) was treated as a random spatial function, following a lognormal distribution. Mantoglu and Wilson (1982) developed a geostatistical technique, the turning bands method, which was used to generate various random ranges of \(K_s\). The random ranges are considered as realizations of a stationary, second-order, spatially random function with a covariance function in the form of:

\[
C(h) = \langle P\theta \cdot \theta h \rangle \sim \exp \left( \frac{-h^2}{\theta^2} \right)
\]

(7)

Here \(P\) denotes the spatially random function in ln(Ks), \(P = P' - \langle P\rangle\) is the fluctuation of \(P\) from its mean \(\langle P\rangle\), \(I_m\) and \(I_p\) are correlation lengths of \(P\) in the \(x\) and \(z\) directions, respectively, \(\sigma^2\) is the variance of \(P\). \(h\) is an offset vector with components \(h_x\) and \(h_z\), and \(r\) is the spatial position. For a given realization, the spatial values of hydraulic conductivity were assigned to relevant nodes in the studied domain. The random distributions of \(K_s\) were incorporated into the flow equations above to simulate water flow and chemical transport in heterogeneous soils. Based on simulation results, stochastic analysis was performed to quantify the effects of soil spatial variability on the transport processes.

3. Results and discussion

3.1 Model details

To demonstrate application of CHAIN_IR, several examples are provided in the following section. For a subsurface drip irrigation field to be simulated, drip lines were buried 15 cm below the soil surface and 50 cm apart. Roots were assumed to be represented by a 30 x 30 cm root zone with a uniform root density distribution. A potential transpiration rate of 0.5 cm d⁻¹ was used during simulations. From the symmetry of the drip lines, a half section of the root zone could be used for numerical simulations, namely a 25 x 80 cm vertical profile with a 15 x 30 cm root zone. The soil hydraulic parameters used in the van Genuchten (1980) form were \(\alpha = 0.05\), \(\beta = 0.4\), \(a = 0.005\) cm⁻¹, \(n = 1.8\), and \(K_s = 5\) cm d⁻¹. The initial pressure head was -500 cm everywhere in the soil profile. Control of irrigation systems was represented by a tensiometer located at the driest possible point within the root zone.
This was at the bottom center of the root zone for flood irrigation and at top right corner of the root zone for drip. Different soil water pressure values were specified from −300 to −3,000 cm to obtain different amounts of irrigation or soil water-crop conditions, such as a full or partial irrigation.

### 3.2 Example 1: drip and flood irrigations without plant stress

To satisfy root uptake at the potential transpiration rate, we set the control pressure to −300 cm or −?!/3 bar). The soil water content at this pressure usually defines cm, the irrigation system was turned on, otherwise it was off. Using CHAIN_IR, subsurface drip irrigation and flood irrigation were simulated for a study period of 16 days. Figure 1 compares the amount of water leaching out of the root zone for the two irrigation systems. The leaching rate of flood irrigation was 3 times greater than that of drip irrigation. Obviously, flood irrigation consumed much more water with a higher potential of groundwater contamination.

### 3.3 Example 2: drip and flood irrigations with plant stress

![Figure 1](image1.png) **Figure 1.** Comparison of the amount of water leaching out of the root zone for the flood and drip irrigation systems under a full irrigation condition.

![Figure 2](image2.png) **Figure 2.** Transpiration rates in the flood and drip irrigation systems under a stressed irrigation condition.

![Figure 3](image3.png) **Figure 3.** Comparison of amount of water leaching out of root zone for flood and drip irrigation systems under deficit irrigation conditions.

![Figure 4](image4.png) **Figure 4.** Comparison of amount of NO leaching out of root zone over 30 days for flood and drip irrigation systems.
For sustainable agriculture, both agriculture productivity and environmental impacts must be taken into account. So stressed (or deficit) irrigation is becoming a useful management practice. Under such conditions, plants may not transpire at the potential transpiration rate; however, certain amounts of water and chemicals may be prevented from leaching out of the root zone. This example was used to compare deficit irrigation using the drip and flood irrigation systems. The controlled pressure was set to -300 cm. The irrigation system was turned on at this level, otherwise it was off. As shown in Figure 2, transpiration in the drip irrigation system is close to the potential transpiration rate, while transpiration in the flood irrigation system is only 75% of the potential transpiration rate. This indicates that crop yield from the flood irrigation may be reduced by 25% relative to that of the drip irrigation. Figure 3 compares the amount of water leaching from the root zone for the two irrigation practices. As the time goes on, the cumulative leaching amount from the drip system approaches a constant, that is, there is no water leaching out of the root zone at all. On the other hand, the total leaching water from the flood irrigation increases linearly with time.

3.4 Example 3: water and chemical transport with nitrification under drip and flood irrigations

This is a comprehensive example to simulate water flow, chemical transport, and root uptake in surface drip and flood irrigation fields. The example applies to the three-step nitrification sequence: \( \text{NH}_4^+ \rightarrow \text{NO}_2^- \rightarrow \text{NO}_3^- \). The input transport parameters for the simulation include longitudinal dispersivity \( D_L = 5.0 \) cm, transverse dispersivity \( D_T = 5.0 \) cm, molecular diffusion coefficient \( D_w = 0.48 \text{ cm}^2 \text{ d}^{-1} \), rate constant for first-order decay of \( \text{NH}_4^+ \) and first-order...
production of NO$_3^-$ in the dissolved phase $\mu_{w} = 0.12$ d$^{-1}$ and in the solid phase $\mu_{s} = 0.12$ d$^{-1}$, rate constant for first-order decay of NO$_3^-$ and first-order production of NO$_3^-$ in the dissolved phase $\mu_{sw} = 2.4$ d$^{-1}$. The simulation involved application of a NH$_4^+$ solution by irrigation to an initially solute-free soil. The applied NH$_4^+$ concentration was assumed to be 10 g kg$^{-1}$. Maximum rates of root uptake were 1 and 2 g kg$^{-1}$ for NH$_4^+$ and NO$_3^-$, respectively. The irrigation systems were automatically operated using tensiometers with the control pressure set to -300 cm. A 30-day growing season was simulated for both drip and flood irrigations. Figure 4 compares the amount of NO$_3^-$ leaching out of the root zone in the flood and drip irrigation systems within the 30 days. Plants were judged to have taken the same amount of water and nutrients from drip and flood irrigated fields. However, the total mass of NO$_3^-$ leaching out of the root zone for the flood irrigation field was 20 times more than that of the drip irrigation field over 30 days. The amount of applied NH$_4^+$ fertilizer in the flood irrigation field was more than twice that in the drip irrigation field.

3.5 Example 4 Water and chemical transport in heterogeneous soils for sprinkler and flood irrigation

Soil saturated hydraulic conductivity fields were generated with different standard deviations of ln $Ks$ (0.5, 0.75, 1.0, 1.25, 1.5). A correlation length of 20 cm was used for both horizontal and vertical directions. For each standard deviation of ln $Ks$, 50 realizations were conducted. These conductivity values were used repetitively for simulating water flow and chemical transport in heterogeneous soils under flood and sprinkler irrigations. While results of water and chemical transport were dependent on the random $Ks$ fields, using an average value of the 50 simulations for each irrigation method was considered to give a good indication of effects of spatial variability under different irrigation methods. Mean values of water and chemical leaching fraction with different $s_{0Ks}$ values under flood and sprinkler irrigation are shown in Figure 5. The fractions were estimated by amount of water and chemical moving out of the domain divided by water and chemical applied. Leaching fractions of water and chemical were shown to increase with increasing spatial variability of $Ks$, which suggested that preferential flow might occur during irrigation. Figure 6 shows standard deviations of resultant water and chemical leaching with different spatial variability for flood and sprinkler irrigation methods. Both data sets showed a consistent increase with increasing spatial variability. Clearly, flood irrigation resulted in higher standard deviations of water leaching fraction than sprinkler irrigation method with $s_{0Ks}$ of 1.25 and 1.5. For chemical leaching fraction, sprinkler irrigation resulted in much smaller standard deviations at all levels of spatial variability of ln $Ks$. Higher standard deviations would increase difficulty in evaluating water and chemical leaching when applying modeling results in field conditions. For low water and chemical leaching with small deviations, sprinkler irrigation would be a favorable choice to prevent groundwater contamination.

Table 1 shows mean values of application efficiency (AE) and standard deviations calculated from the 50 simulations under the different irrigation methods. Application efficiency is defined as amount of water taken by roots over total amount of water applied. Apparently, the soil spatial variability has little effect on mean values of water root uptake for the three irrigation methods on both soils. This was unexpected since it is known that roots usually take more water from wetter areas. So, the effect of spatial variability on root uptake was masked even though there were differences of water distributions in the root zone. Irrigation uniformity is considered an important factor of irrigation performance and generally characterized by Christiansen uniformity coefficients (CUC). CUC was calculated by $CUC=100[1-(s/Mn)]$, where $s$ is the absolute value of deviation from the mean $(M)$ of applied water observations, and $n$ is number of observations. The distribution is uniform when CUC equals 100. Table 2 presents mean values and their standard deviations of CUC at 10$^0$ and 30$^0$ days in the root zone under various simulation conditions. Increasing variability reduced irrigation uniformity at both 10$^0$ and 30$^0$ days for both flood and sprinkler irrigation methods. Compared with sprinkler irrigations, flood irrigation resulted in higher CUCs at early simulation period and lower CUCs at the end of simulations for both soils. Tables 1 and 2 show that standard deviations of AE and CUCs increase consistently with increasing variability of $Ks$.

4 Conclusions

As advanced computation methods are being developed, computer models are increasingly becoming efficient and economical tools for studying subsurface transport processes. In this study, an irrigation simulation model, CHAIN_IR, was introduced. This model can be used to quantitatively describe water flow, root uptake, and chemical movement in various irrigation fields. The model is...
especially useful to simulate the three-step nitrification chain: \(\text{NH}_4^+ \rightarrow \text{NO}_2^- \rightarrow \text{NO}_3^-\), and flow transport in heterogeneous soils under different irrigations. Through computer modeling of flood and drip irrigations, the following conclusions were drawn for the examples. For unstressed or full irrigation, water leaching from the root zone for flood irrigation was 3 times that for drip irrigation. For deficit irrigation, water by root uptake under flood irrigation was only 75% of that under drip irrigation. Water leaching from the root zone increased linearly with time for flood irrigation. In contrast, after a while no water leached from the root zone for drip irrigation. Since the frequency of drip irrigation was higher than that of flood irrigation, variation of soil root water distributions with time were more uniform for drip irrigation than for flood irrigation. For drip irrigation there was more than 20 times less \(\text{NO}_3^-\) being leached from the root zone, compared with flood irrigation.

To simulate water flow and chemical transport in heterogeneous soils under different irrigations, random values of log of saturated hydraulic conductivity \((\ln K_s)\) were generated using a geostatistics method for different standard deviations of \(\ln K_s\). Then the random values were incorporated into the irrigation model to study effects of spatial variability on the flood and sprinkler irrigation methods. Stochastic analysis based on the simulation results showed that water and chemical moved deeper in heterogeneous fields than in the homogeneous field.

With the same spatial variability of \(K_s\), flood irrigation resulted in higher leaching fraction of water and chemical, compared with the sprinkler irrigation. Sprinkler irrigation was less affected by spatial variability of \(K_s\) and should be a preferable to reduce risks of deep leaching and groundwater contamination.

### References


### Table 1. Mean values of application efficiency and standard deviations \((s)\) calculated from 50 realizations

<table>
<thead>
<tr>
<th>(s)</th>
<th>0.5</th>
<th>0.75</th>
<th>1.0</th>
<th>1.25</th>
<th>1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flood</td>
<td>Mean</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
<td>0.46</td>
</tr>
<tr>
<td>s</td>
<td>0.0015</td>
<td>0.0021</td>
<td>0.0025</td>
<td>0.0029</td>
<td>0.0035</td>
</tr>
<tr>
<td>Sprinkler</td>
<td>Mean</td>
<td>0.43</td>
<td>0.43</td>
<td>0.43</td>
<td>0.43</td>
</tr>
<tr>
<td>s</td>
<td>0.0019</td>
<td>0.0029</td>
<td>0.0038</td>
<td>0.0048</td>
<td>0.0056</td>
</tr>
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</table>

### Table 2. Means and standard deviations \((s)\) of Christiansen uniformity coefficients at 10 and 30 days

<table>
<thead>
<tr>
<th>(s)</th>
<th>0.5</th>
<th>0.75</th>
<th>1.0</th>
<th>1.25</th>
<th>1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>10th Flood</td>
<td>Mean</td>
<td>97.5</td>
<td>97.4</td>
<td>97.2</td>
<td>97.1</td>
</tr>
<tr>
<td>s</td>
<td>0.6</td>
<td>0.88</td>
<td>1.2</td>
<td>1.6</td>
<td>2.0</td>
</tr>
<tr>
<td>Sprinkler Flood</td>
<td>Mean</td>
<td>94.8</td>
<td>94.6</td>
<td>94.2</td>
<td>93.5</td>
</tr>
<tr>
<td>s</td>
<td>0.96</td>
<td>1.5</td>
<td>2.2</td>
<td>3.0</td>
<td>3.7</td>
</tr>
<tr>
<td>30th Flood</td>
<td>Mean</td>
<td>95.4</td>
<td>95.5</td>
<td>95.7</td>
<td>95.7</td>
</tr>
<tr>
<td>s</td>
<td>0.68</td>
<td>0.85</td>
<td>1.1</td>
<td>1.1</td>
<td>1.5</td>
</tr>
<tr>
<td>Sprinkler Flood</td>
<td>Mean</td>
<td>97.0</td>
<td>96.9</td>
<td>96.7</td>
<td>96.4</td>
</tr>
<tr>
<td>s</td>
<td>0.89</td>
<td>1.2</td>
<td>1.7</td>
<td>2.1</td>
<td>3.3</td>
</tr>
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Strategies for managing water scarcity in China until 2030

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Abstract

Analysis of the balance of supply and demand shows that per capita freshwater availability in China is increasingly in short supply. Less water will be available for irrigation because of the rapidly increased demands for freshwater for industrialization and urban domestic use. To feed her 1.6 billion population in 2030, while keeping sound ecosystems and environment, there is an urgent need for China to produce more food with less water. This paper presents objectives for sustainable water use and agricultural development in China and discusses the strategies for managing water scarcity in 2030. Firstly, great efforts in developing and applying on-farm water saving irrigation (WSI) practices should be exerted. The widespread adoption of WSI techniques will provide an opportunity for efficient water use on a large scale because it impels every farmer to use water carefully, to capture the return flow, harvest the rainfall water and control the percolation losses. Secondly, the modernization and rehabilitation of irrigation schemes must be speeded up to improve water use efficiency and irrigation reliability. Thirdly, more attention should be paid to institutional development to maximize the effects of agricultural infrastructure, and of successful research on, and dissemination of, new technologies. Sound water pricing mechanisms will impact on reduction of demands, increased supply, facilitation of reallocation among water use sectors, and increased managerial efficiency. As the country-level, massive regional differences in water scarcity are hidden behind the average figures. Strategies for sustainable water use should be in line with the regional characteristics, distribution of water resources and the regional water balance. Equal attention would be paid to improving irrigation works and management, water conservancy and agro-techniques.

Key words: Freshwater availability, strategy for managing water, water saving irrigation.

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1 Introduction

China is feeding about 22% of the world population with about 6% of the freshwater and 9% of the arable lands in the world (Qian and Zhang, 2001). It is estimated that average access to water resources will decrease to 1760 m$^3$ per capita in 2030, which implies that China is becoming a country short of water (Liu, 2000; Qian and Zhang, 2001). Furthermore, the country-level data hides massive regional differences in water scarcity behind the average figures, and water resources do not match the distribution of farmland. Regional and seasonal water shortages are very serious.

In her history, China had been confronted with water shortage for centuries, which suggests a deep cultural experience with this resource. So, many people disagree with Lester Brown’s alarming diagnosis of China’s water shortage (Heilig et al., 2000; Huang et al., 1997; Liu, 2000). However, the past success in water management is certainly no guarantee for the aiming at increasing water and land productivity. Widespread adoption of on-farm WSI practices and water pricing provide an opportunity for challenges of the future. To feed her 1.6 billion population in 2030, China has to increase total agricultural production by almost 30%. Most authorities agree that irrigation must play a greater proportionate role in meeting future food needs than it has played in the past (DRWM, 2001; Heilig et al., 2000; Qian and Zhang, 2001; Seckler et al., 1999). On the other hand, current farming in China is very intensive and available water for the agricultural sector is decreasing. This arises because of water pollution resulting from dramatic progress of industrialization and urbanization, rising riverbeds, shrinkage of lakes and declining groundwater tables. As irrigation consumes the largest amount of freshwater, so it is assumed that a great deal of water could potentially be saved in this sector because of low irrigation efficiency and the surplus water of south China. Irrigated agriculture is likely to become the “victim” of water shortage.

In the past two decades, China has pioneered some water saving policies and WSI techniques, efficient water use on a large scale. High-level support policies for WSI should help maximize benefits of the agricultural infrastructure and of
further dissemination of research into new technologies. There are many success stories about “real” water savings in China. However, both population and income growth has been influencing the balance of supply and demand for staple grains and freshwater and will continue to in future. Considering national economy development and improvement of people’s living standards, irrigation is not likely to get more water (Table 1). Water shortage will be the “bottleneck” for future agricultural development in China (Brown, 1995; Brown and Halweil, 1998; DRWM, 2001; Qian and Zhang, 2001; Seckler et al., 1999; Serageldin, 1999).

Table 1. Forecasting water supply capacity and available water for agriculture

<table>
<thead>
<tr>
<th>Items</th>
<th>Unit</th>
<th>2000 (datum)</th>
<th>2010 Supply</th>
<th>2010 Demand</th>
<th>2030 Supply</th>
<th>2030 Demand</th>
</tr>
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<tbody>
<tr>
<td>Total water supply capacity</td>
<td>Billion m$^3$</td>
<td>559.1</td>
<td>605.7</td>
<td>613.4</td>
<td>699.0</td>
<td>711.9</td>
</tr>
<tr>
<td>Available water for agriculture</td>
<td>Billion m$^3$</td>
<td>386.9</td>
<td>397.9</td>
<td>418.6</td>
<td>420.0</td>
<td>463.4</td>
</tr>
<tr>
<td>Available water for irrigation</td>
<td>Billion m$^3$</td>
<td>360.0</td>
<td>366.0</td>
<td>381.9</td>
<td>378.0</td>
<td>417.1</td>
</tr>
<tr>
<td>Ratio of agricultural water use</td>
<td>%</td>
<td>69.2</td>
<td>65.7</td>
<td>68.2</td>
<td>60.1</td>
<td>65.0</td>
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<tr>
<td>Ratio of irrigation water use</td>
<td>%</td>
<td>64.3</td>
<td>60.4</td>
<td>62.3</td>
<td>54.1</td>
<td>58.6</td>
</tr>
</tbody>
</table>

Guaranteed food security, accompanying sustainable economic development, sound ecosystem and environmental management will not be possible without advanced irrigation. Sustainable agricultural development must rely on sustainable water use in China. The national policy is to develop irrigated agriculture without taking more fresh water (DRWM, 2001) so that increases of available water could be used for other sectors. Agricultural products will be increased mainly through three ways: (1) increasing effectiveness of irrigation and then transferring some water to increase irrigated areas, (2) increasing the multiple cropping index for irrigated lands with similar water use, and (3) improving farming techniques and increasing water productivity in rain-fed areas.

2 Objectives for managing water scarcity in the 21st Century

The ultimate goal in managing water scarcity is to guarantee food security for China while maintaining sustainable economic development with sound ecosystem and environmental management. Main objectives are:

- Reforming water management systems to reduce institutional friction between various administrative levels concerning planning, financing, construction and maintenance of water-related infrastructure. Policies and rules for water saving, a unified management of water resources and water pricing must be carried out. Not only should water scarcity be signaled to consumers, but incentives for water saving should also be given to water users.
- Notably improving irrigation facilities, canal systems and on-farm water management practices to increase irrigation efficiency, water supply reliability and irrigation water productivity. The irrigated area will reach 58 million ha and 63.3 million ha in 2010 and 2030, respectively. The irrigation water use efficiency will be increased by 5-7% and 7-10%, in two stages, and the irrigation water quota should be reduced to 618 mm and 597 mm, respectively, in 2010 and 2030. Increased irrigation areas will mainly get water from water savings of current irrigated farmlands.
- Improving rain-fed cultivation practices. In addition to cultivating drought-tolerant varieties and reducing soil evaporation and leaf transpiration through biological and agricultural measures, comprehensive measures will be introduced to increase rainfall use by 3-5% and 5-7% in two stages.

To reach these objectives, efficient water use in agriculture must be developed in line with the following principles:
- Load-carrying capacities of water and land resources are the basis of both national economy and agriculture. Population, resource use and ecosystems protection should be brought into line sustainable water use.
- Natural and social conditions vary from place to place in China. Main problems related to development of efficient water use in agriculture should be researched separately and local experience should be summarized.
- Efficient water use in agriculture would be developed step by step according to China’s ability at different stages. Action plans should be carried out with future aims but be based on the current situation regarding socio-economic and management levels of different regions and their development stages.
- Overall planning is needed for rational development, optimum allocation, efficient use and effective protection of water resources.
- Equal attention should be paid to infrastructure and on-farm systems, project and institutional measures, irrigation practices and agro-techniques, modern techniques and traditional experience.
- Full use of rainfall water is a prerequisite for efficient water use in agriculture. All measures aim at increasing water and land productivity.
- As farmers are main group of water consumers, farmers should benefit from development of
efficient water use in agriculture when they are encouraged to use less water.

3 Research and implementation of WSI techniques

3.1 On-farm WSI techniques

While achievements have been made in research into on-farm WSI techniques in China, practicable techniques are still lacking. Nowadays, research on WSI claims a top priority in China to avoid reduction of crop yields or other negative impacts resulting from WSI practices. Systematic research should continue into crop-water relations, physiological mechanisms of drought tolerance, evapotranspiration (ET) under limited water supply or with ground covers and crop water production functions. This research will support improvement of irrigation practices including alternate wetting and drying irrigation (AWDI) for rice, partial irrigation, regulated deficit irrigation and controlled root-divided alternate irrigation. Research into transformation of precipitation, surface water, groundwater and soil moisture along with movement of water in the soil-plant-atmosphere continuum should be strengthened to increase water productivity. Field water application techniques must be improved. In particular, low-cost irrigation equipment should be developed.

Pilot experiments are recommended for research into WSI techniques and professional institutes are encouraged to collaborate with field experiment stations. Optimum groupings of workers linked to irrigation, agro-techniques and biochemistry represent valuable practices. Comprehensive research also includes regulation of cropping patterns and development of crop varieties with better tolerance for drought, cool seasons and saline conditions.

3.2 Dissemination and implementation of WSI practices

Not only should farmers understand technical essentials of WSI practices, but they should be schemes in total, each with a design irrigation area exceeding 20,000 ha. The total irrigation area of large-sized irrigation schemes is more than 15.7 million ha, accounting for about 11.3% of the total cultivated area. Grain production from the area makes up 22% of national grain output, and yields are as high as 6.75 t/ha, which is 1.5-3.0 t/ha higher than the average (DRWM, 2001). So, it is the main force of agricultural production, national grain commodity supply as well as being a major component the agricultural economy of China. However, most of those irrigation systems were constructed in the 1950’s and 1960’s, designed to a low standard, with aged structures and imperfect field works, resulting in low irrigation water use efficiency. From 2001, the program of modernization and rehabilitation of the existing large-sized irrigation schemes was put into effect, leading to higher water use efficiency and higher water productivity. After the modernization and rehabilitation of the 402 irrigation schemes over a period of 15-20 years, 33 billion m$^3$ of irrigation water will be saved compared with existing water consumption. Then real water savings will support expansion of effective irrigation area, improvement of irrigation reliability and increase of multiple cropping indices. The grain production from the large-sized irrigation districts will be more than 160 million tons per year and account for 27% of national grain output. According to the program, not only will the probability of guaranteed irrigation be improved, but also the effective irrigation area will be increased to 19.3 million ha. In addition, experience from modernization of large-sized irrigation systems will be introduced to the modernization of medium and small-sized irrigation schemes, providing a foundation for sustainable water use and agricultural development.

This program represents systematic engineering. Equal attention should be paid to infrastructure and on-farm systems, project and institutional measures, irrigation practices and agro-techniques, modern techniques and traditional experiences. Integrated water management and combined use of surface water and groundwater are promoted. Designers are encouraged to build “melons-on-the-vine” irrigation systems with function of “storing, diversion and lifting”.

4 Institutional development

4.1 High-level policy support

Many reports suggest that the “core problem” for China is institutional development to manage water scarcity (Barker et al., 2001; Heilig et al., 2000; Nyberg and Rozelle, 1999). On the other hand, the Chinese have invested in research on WSI practices and supported policies and practices that promote real water savings. Institutional development has gone beyond the traditional narrow concept of organizational and manpower strengthening and training. The experience, especially the post-1978 reforms, demonstrates the importance of incentives and a conducive institutional framework in maximizing the benefits of agricultural infrastructure, and of successful research into and dissemination of, new technologies.

Nevertheless, it is necessary to recognize that China already has relatively sound laws and institutions. Institutional “software” deserves equal attention with physical “hardware” for irrigation systems. A series of policies have been drawn up, such as the Water Law, Water Resources Protection Law and Water Charge
4.2 Funding policy

In addition to the program for modernization of large-sized irrigation schemes, financial support from central government is available each year for around 60 counties. These are selected as the “key counties” for developing efficient water use agriculture. In addition, around 30 medium-sized irrigation schemes are to be improved, focusing on increasing conveyance efficiency and there are about 120 demonstration projects as examples of implementing comprehensive measures for efficient water use. Not only does this program improve irrigation facilities, but it also pays great attention to capacity building and institutional development. To ensure success of the ambitious program and the most cost-effective option for the tremendous investment, priority is given to those locations with wider adoption of WSI practices, more incentives for water savings and better institutional management. Irrigation agencies should search for technical support from universities and professional institutes in planning protection and use of water resources, design of irrigation systems, research and implementation of comprehensive measures for real water savings, capacity building and institutional management.

4.3 Water pricing

Most people agree that water pricing has an effect on reducing demand, increases supplies when marginal projects become affordable, facilitates reallocation among water users and increases managerial efficiency. But, the mechanisms are more important than the pricing, and effective pricing mechanisms should focus on incentives for farmers to value water resources and use water carefully. On the one hand, water price might be significantly increased but the irrigation water price should not simply reflect all development, operation and management costs because Chinese farmers are still poor. Water prices for each alternative use – irrigation, industry, cities and hydropower will be different, and will vary in different seasons and for different quantities. When water is short, the price will rise and the price for extra delivery will be much higher than the standard price. Water measurement also provides an opportunity for volumetric water charges, but in China, water consumption is not usually measured at the level of individual farms. Instead, measurements are typically taken for groups of farm households, with the size of these groups being quite variable within an irrigation system and across different irrigation systems. This creates potential free-rider problems. Hence, decisions on water consumption require some degree of collective action. Fortunately, collectivized agriculture was practiced for many years in China, and farmers understand the importance of collective action for irrigation, land reclamation and flood control, even after the wave of great reform (Barker et al., 2001).

It should be remembered that water pricing is a double-edged sword. Sometimes, the benefits from WSI practices could not be well coordinated between farmers, irrigation agencies and government. If an agency were not able to transfer water savings from irrigation to more beneficial water uses, the agency would send as much water as possible to water measurement points. If farmers worry about getting less water than their fair share in a group, they might take too much water. So a pricing mechanism, combining new institutional frameworks with farmer participation, promises incentives for both farmers and agency to save water.

4.4 Farmer irrigation association (FIA)

Recently, it is very popular for governments to transfer greater responsibility to user groups for irrigation system management in hope of improving irrigation efficiency (Nyberg and Rozelle, 1999). The World Bank and other institutions have introduced the Self-Financing Irrigation and Drainage District (SIDD) model to developing countries, over the past several years. However, this model appears to have difficulties because agricultural water fees are not able to cover all costs. Alternative recommendation in China is the Farmer Irrigation Association (FIA). Sizes vary but each has a chairman who is elected by a “one family one vote” system and who appoints an irrigator to measure the volume of “inflow”. The irrigator works with people from an irrigation agency and allocates water within the group. The chairman organizes the “collective action” of building and maintaining on-farm irrigation systems, protecting irrigation facilities, purchasing irrigation water, storing extra deliveries, catching return flows and harvesting rainwater. The water fee is paid directly to the irrigation agency and farmers see what they pay so they are happy to minimize water use. Experiences will be summarized, and government will play a more important role in fostering FIAs.
5 Regional strategies

It is estimated that the total deficit at a national level will be around 13 billion m$^3$ in 2030; however, the water shortage in the North China Plain will be as high as 25-46 billion m$^3$ (Qian and Zhang, 2001). This indicates that there appears to be limited conflict over supply and demand of water resources, and national statistics hide massive regional differences in water scarcity in China. In fact, regional water shortages are experienced by all provinces, such as western parts of Northeast China, south of Xinjiang Autonomous District and in the coastal areas of Southeast China. Even in the most water abundant areas like Hubei, Hunan and Jiangsu Provinces, droughts frequently alternate with water-logging. It is widely recognized that around one-third of the population lives in regions that should be classified as regions of absolute water scarcity (Brown and Halweil, 1998; Seckler et al., 1999). So, China must create effective strategies and promote efficient irrigation practices for sustainable water use, in line with regional characteristics, distribution of water resources and regional water balances.

The “grain-cash-forage crops” farming system has not developed in China and forage crops, especially drought-tolerant forage crops, have been ignored. On the other hand, there are changing food habits associated with income growth and urbanization (Denning and Mew, 1998). It is expected that regional water scarcity would be alleviated and the overall water productivity would be increased through readjusting agricultural economic structures, especially by developing aquatic product industries and stock raising, in the light of local conditions.

In the Yellow-Huai-Hai Plain, where per capita fresh water is less than 500 m$^3$ per year, it has become one of the most water-short regions in the world (Brown and Halweil, 1998; Seckler et al., 1999). The planting area of winter wheat should be reduced, and support from government is encouraging growing cash crops. Deficit irrigation should be used for the dominant wheat and maize crops. Priority will be given to this region for modernization of irrigation schemes and implementation of comprehensive agronomic and irrigation measures. Sustainable water use would be reached with best use of rainfall and scientific use of Yellow River water combined with slightly salty water, together with balancing depletion and recharge of ground water. After North China benefits from the “Water Transfer from South to North”, then aquifers will be gradually recharged.

In Northwest and Northeast China, rain-fed agriculture should be promoted, and irrigated areas should not be increased any more to ensure necessary water use for ecosystems (DRWM, 2001). Cultivated land should be turned over to pasture and water saving irrigation would be adapted to develop pasture-land. Paddy fields would be reduced as much as possible and the crops that consume less water, such as maize, sorghum and millet should be promoted. Except for areas already having investments in canal linings and land leveling, movable sprinklers will be used widely.

Southern parts are relatively wet, but adoption of WSI practices is meaningful. The climate allows an increase in the multiple cropping index in irrigated lands, but the irrigation water diversion can not be increased. AWDI techniques for rice should be widely used in this area to increase water and land productivity and save water for other regions and other users. Experiences from Hubei and Hunan provinces indicate that AWDI practice is quite useful to improve the low production paddy fields with poor soil aeration and subsurface water-logging (Li et al., 1999). Implementation of WSI techniques in the South would play an important role in increasing food production capacity and changing the situation of “grain transfer from north to south”, so reducing water demand in the North (Li, 2001; Li et al., 1999).

6 Conclusions

It is widely recognized that China is facing severe water scarcity and the population, ecosystems and income growth will remain a major force to supply of freshwater in future. However, there is no need for nervous pessimism or blunt doomsday scenarios. According to the discussion in this paper, sustainable water supply and sustainable agricultural development could be realized mainly associated increasing effectiveness of irrigation and then transferring some water to increase irrigated area, increasing multiple cropping index in irrigated lands with similar water use, and improving farming techniques and increasing water productivity in rain-fed cultivation areas.

In addition, China will find that it is more difficult to sustain farmers’ interest in farming with the progress of her joining the WTO because of the “free trade” in agricultural production. To find the incentives for agriculture and for producing more food with less water, China has set some strategies for management of water scarcity even though many scientific issues have been addressed and the application of WSI techniques in some regions is still very difficult because of both physical and ideal problems. Not only should the water consumers be signaled water scarcity, but the incentives for water saving should be also given to water users. A wide cooperation of water and agricultural scientists is
requested in the research and practice of WSI techniques, and the forceful support from government is required.

References


Irrigation scheduling effects on cotton growth and yield for drip irrigation under plastic mulch

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Abstract
Effects of different irrigation schedules were investigated for drip irrigation of Cotton under mulch, to determine optimal crop yield, quality and water use efficiency. The field experiments were conducted at Shihezi Experimental Station for Soil Amelioration, Xinjiang, from April to October 2000, using experimental plots each 88.3m long and 1.7m wide. Drip laterals were placed under plastic mulch in alternate mid-rows. Three irrigation levels were designated for each growing stage, making eleven treatments in total, with 3 replicates. Regression analysis showed that a quadratic relationship best described lint and seed Cotton yields in relation to irrigation amount. The irrigation amount corresponding to maximum lint yield was 385 mm, which included three irrigations with 55.5 mm to ensure crop emergence. Excessive irrigation or severe water deficit could reduce Cotton quality. Peak seed cotton yield was 6380 kg/hm$^2$. The cotton was irrigated 9 to 11 times, with 25 mm to 30 mm each time. Peak water use efficiency was of the order 0.55 kg/m$^3$.

Key words: Cotton, drip irrigation under plastic mulch, irrigation schedule

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1 Introduction
Cotton is the most important economic crop in the Xinjiang Uygur Autonomous Region of northwest China. Because rainfall in the area is very limited, there is a great deal of concern about how to meet the demands for irrigation water. Water-saving irrigation techniques are becoming more and more important. A new irrigation method, drip irrigation under plastic mulch, has been widely adopted in the region to save water and increase cotton yield.

Drip irrigation systems can precisely apply water to crops at low pressure, and thus save water and energy compared to other irrigation systems. Dasberg and Or (1999) gave a critical overview of the applications of drip irrigation to the main branches of agriculture and horticulture. Under Israeli conditions, drip irrigation is more efficient than sprinkling, linear-move or center-pivot techniques, even without taking into account the increase in yield that often results from use of drip irrigation. Bauer et al (1997) studied the effects of subsurface drip irrigation, lateral placement, and N-application method on cotton. They indicated that for subsurface irrigation systems, alternate mid-row placement of laterals was effective in supplying water and N to cotton. Norton and Silvertooth (2001) indicated that an increase in lint yield of approximately 250 lbs. lint/acre was obtained in a drip irrigation system compared to a conventional furrow-irrigated cotton production system in the Marana Valley. Ayars et al (1999) reviewed the subsurface drip irrigation research on tomato, cotton, sweet corn, alfalfa, and cantaloupe over a period of 15 years. Their results demonstrated that drip irrigation resulted in a significant increase in yield and water use efficiency (WUE) for all crops.

Drip irrigation has been used under mulch in some crops (Tiwari et al, 1998; Shrivastava et al, 1994). With the development of low cost driplines, use of drip irrigation under plastic-mulch in Xinjiang has extended very quickly. More than 100,000 ha of cotton is currently grown with drip irrigation under plastic-mulch. The growing conditions for cotton are quite different in plastic-mulched compared to non-mulched fields, so water use and irrigation scheduling should also be different. The objective of the study was to investigate the effect of different irrigation schedules for drip irrigation under plastic-mulch on cotton growth, yield and quality. Through this research we hope to increase both cotton yield and WUE.

2 Materials and methods
The experiment was conducted at Shihezi Experimental Station for Soil Amelioration (44°51' N, 85°34' E) in Xinjiang, China from April to October of 2000. An annual average rainfall of 140 mm characterizes the climate of the region, with an average evaporative demand of 1790 mm
and an average frost-free period of 160 days. The depth of groundwater is about 3.0 m, and the soil is sandy loam.

The experimental area was about 1.5ha. The area was divided into experimental plots with dimensions 88.3m long and 1.7m wide. There were four rows of plants in each plot, and the plots were mulched with plastic film. The distance between rows was 30cm, 50cm, and 30cm. Drip laterals were placed under the plastic mulch in alternate mid-rows. The distance between drip laterals was 80cm. Cotton was planted on April 22.

To guarantee emergence of the cotton, the plots were irrigated three times between April 22 and May 2.

The cotton-growing season was divided to 5 stages, namely vegetative, bud, early flowering, late flowering, and boll opening. Three irrigation levels were designated at every growing stage. Level 1 means that the irrigation regime was same as the control treatment (T1). Level 2 represented irrigation intervals being longer than the control by 2 days for the vegetative stage, 1 day for the bud stage, 0.5 day for the early flowering stage, and 1 day for the late flowering stage. Level 3 represented irrigation intervals being longer than the control by 3 days for the vegetative stage, 2 days for the bud stage, 1 day for the early flowering stage, and 2 days for the late flowering stage. A summary of irrigation times and amounts is shown in Table 1. In total there were eleven treatments with 3 replicates.

Two rows at the middle of each plot were used to measure the status of cotton growth and yield. Before and after irrigation, soil water contents were monitored to a depth of 100 cm, in 20-cm increments, by gravimetric sampling of each treatment. Soil water contents were measured at 0, 40 and 65 cm from laterals then averaged for each treatment. Cotton water use was calculated using the water budget equation.

Table 1. Experimental design

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Vegetative</th>
<th>Bud stage</th>
<th>Early flowering stage</th>
<th>Late flowering stage</th>
<th>Irrigation (mm)*</th>
<th>Irrigation times*</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>425</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>T2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>390</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>T3</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>299</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>T4</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>365</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>T5</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>404</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>T6</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>338</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>T7</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>330</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>T8</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>338</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>T9</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>327</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>T10</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>266</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>T11</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Includes three irrigations with 56mm from sowing to emergence.

Fig. 1 The relationships of irrigation amount with lint yield and seed cotton yield

Fig. 2 The relation between water use efficiency and irrigation amount
3 Results and discussions

3.1 Relationship between cotton yield and water use

Regression analysis showed that there was a quadratic relationship between lint and seed cotton yield with amount of irrigation water (Figure 1). Results also showed that cotton yield decreased when the amount of irrigation exceeded a certain range. According to the regression results, maximum lint yield occurred with an application of 385mm of irrigation water, including the water applied between sowing and emergence. Lint yield was much lower when 330mm of irrigation water was applied, indicating that timing of irrigation had a large effect on cotton yield.

The amount of water needed for maximum seed cotton production was more than the amount needed for maximum lint yield. This indicates that the additional water needed to maximize seed cotton yield actually resulted in a reduction in lint yield. The WUE, expressed as lint yield per cubic meter of irrigation water applied, reached its highest value at about 350mm of irrigation water (Figure 2). To obtain high cotton yield and WUE with drip irrigation under a plastic-mulch system, the irrigation amount should be between 350mm and 385mm in this region.

3.2 Effect of different irrigation treatments on cotton growth

Irrigation amount and timing had a large effect on cotton growth and effects of water stress on different parts of the plant was not the same. For example, long-term water deficit in treatment T11 led to a decrease in cotton height (Figure 3). However, moderate water stress in treatment T10 had little effect on plant height. Similarly, moderate water stress had little effect on stem diameter of cotton (T10 in Figure 4), but long-term severe water stress also resulted in a reduced stem diameter (T11 in Figure 4). In contrast, main root length increased as irrigation water decreased (Figure 5), which showed that soil water deficit can stimulate root growth and make it absorb more water from deep soil.

Irrigation treatments also affected the ratio of bud drop and boll shedding. From field observations made on August 26, the ratio of bud drop and boll shedding was higher in treatments that received more irrigation water at the early flowering stage (T1, T6, and T8). This was also true in treatments that had a continuous...
water deficit during the growing season (T3 and T11) (Figure 6). Results indicated that both under-irrigation and over-irrigation could increase bud drop and boll shedding, which agrees with results obtained in Turkey by Cetin and Bilgel (2002). At harvest, there were 4.7 times more bolls in the T4 treatment at harvest than in the T11 treatment.

Table 2. Cotton yield and quality for drip irrigation under mulch in 2000

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Staple length (cm)</th>
<th>Lint (%)</th>
<th>Seed cotton yield (ton/ha)</th>
<th>Lint yield (ton/ha)</th>
<th>WUE* (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>5.33</td>
<td>36.4</td>
<td>5.00</td>
<td>1.82</td>
<td>0.428</td>
</tr>
<tr>
<td>T2</td>
<td>6.07</td>
<td>36.1</td>
<td>6.38</td>
<td>2.30</td>
<td>0.591</td>
</tr>
<tr>
<td>T3</td>
<td>5.80</td>
<td>37.3</td>
<td>3.48</td>
<td>1.30</td>
<td>0.435</td>
</tr>
<tr>
<td>T4</td>
<td>5.80</td>
<td>40.9</td>
<td>6.03</td>
<td>2.46</td>
<td>0.676</td>
</tr>
<tr>
<td>T5</td>
<td>6.10</td>
<td>37.8</td>
<td>5.14</td>
<td>1.94</td>
<td>0.482</td>
</tr>
<tr>
<td>T6</td>
<td>5.90</td>
<td>36.8</td>
<td>4.09</td>
<td>1.51</td>
<td>0.446</td>
</tr>
<tr>
<td>T7</td>
<td>5.63</td>
<td>37.8</td>
<td>5.90</td>
<td>2.23</td>
<td>0.675</td>
</tr>
<tr>
<td>T8</td>
<td>6.13</td>
<td>41.2</td>
<td>4.59</td>
<td>1.89</td>
<td>0.572</td>
</tr>
<tr>
<td>T9</td>
<td>5.73</td>
<td>41.6</td>
<td>3.43</td>
<td>1.43</td>
<td>0.422</td>
</tr>
<tr>
<td>T10</td>
<td>6.03</td>
<td>36.2</td>
<td>5.27</td>
<td>1.91</td>
<td>0.583</td>
</tr>
<tr>
<td>T11</td>
<td>5.90</td>
<td>36.2</td>
<td>3.20</td>
<td>1.16</td>
<td>0.436</td>
</tr>
</tbody>
</table>

* WUE, expressed as lint yield per m³ of irrigation water applied

3.3 Effect of irrigation amount and time on cotton yield

The highest yield in our experiment was obtained in the T4 treatment. The lowest yield was in T11. Although T1 received the maximum amount of irrigation water, its lint yield was only 1.82 ton/ha. The lint yields of T4, T2, and T7 were significantly higher than that of T1, although those treatments received 22-36% less irrigation water than T1. Lint yields in T5, T8 and T10 also tended to be higher than T1, though the differences were not necessarily significant. These results demonstrate that full water supply during the growing season did not necessarily result in maximum yield. Excess water results in an increase in leaf growth and causes a decline in canopy ventilation and light transmittance. These factors probably contributed to the increase in bud drop and boll shedding that we observed in the fully watered treatment (Figure 6).

In the treatments with high lint yield (T4, T2, and T7), the amount of time between irrigation periods was 1 to 2 days longer than the control treatment (T1), especially at the early flowering stage. This indicates that moderate water deficit was beneficial to lint yield at some stages of plant growth. The results also showed that the same amount of irrigation water resulted in different lint yields depending on growth stage of the plant. For example, the amount of water applied to T9 and T6 was similar with T7, but their lint yield was much lower than T7 (Table 2). The main reason was that the time between irrigation was too long at some stages, resulting in an increase of bud drop and boll shedding.

3.4 Cotton quality in different irrigation treatments

In addition to cotton yield, irrigation treatments also affected cotton quality. For example, in the fully watered T1 treatment, staple length was shorter than any other treatment (Table 2). Lint percentage in the T1 treatment was also among the lowest observed. At the opposite extreme, treatment T11 suffered water stress during the whole growing season. Its staple length and lint percentage were also among the poorest measured. These results demonstrate that either excessive water supply or severe water deficit may reduce cotton quality.

4 Conclusions

Cotton yield and quality are very sensitive to irrigation. In drip irrigation under plastic-mulch system, there is a quadratic relationship between lint or seed cotton yield with amount of irrigation water. Too much or too little irrigation leads to a decrease in cotton yield and quality. From emergence to bud stage, one or two irrigations of about 45mm of water are sufficient for the needs of the cotton crop. Over irrigation can cause excessive vegetative growth and bud drop. The bud to bloom period is a very important period for high lint yield. Proper irrigation can coordinate cotton growth and makes more photosynthate go to reproductive organs. Irrigation intervals of 7 to 10 days are best during this period. A total of 9 to 11 irrigation periods are recommended, each time applying 25mm-30mm water, to maximise lint yield and WUE in cotton.

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