THESIS

BASIC METHODS OF IRRIGATING
GREENHOUSE CARNATIONS

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY JORGE T. CAPARAS ENTITLED BASIC METHODS OF IRRIGATING GREENHOUSE CARNATIONS BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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INTRODUCTION

Since the introduction of the carnation in the United States, its production has jumped from an inconsequential figure to the sizeable gross return of 20 million dollars realized in 1949 (12). In Colorado, carnation production has grown steadily, and in 1949, the gross return from carnations was conservatively placed at three million dollars (12). Unfortunately, production costs have also increased through the years. Reliable figures concerning the cost of keeping one square foot of carnation bench space in production are not available. However, a study conducted at the Colorado A & M Research Greenhouses showed that the annual cost of hand watering—a widely used method in Colorado—is approximately 10 to 14 cents per square foot of bench space.*

As a result of increasing carnation production, competition among growers is not confined entirely to Colorado. An indication of the keenness of the competition

* Study conducted by the writer in 1953.

with which growers are confronted may be gained by noting that in 1949, only one-third of the total production in Colorado was marketed locally (12). The remainder had to be shipped to other parts of the country where it was subject to a greater degree of competition. As in other competitive enterprises, efforts have been directed at reducing production costs and in improving the quality of the product marketed. Of the factors which influence the cost of production, a change in the method of irrigation presents the greatest possible savings with the least capital outlay. Accordingly, more and more growers have done away with hand watering methods. At present growers concede that a satisfactory watering system must satisfy the following requirements: 1) its cost must be within reasonable economic limits; 2) it must be simple and easy to install and operate; 3) water application should be uniform and should be accomplished with a minimum wetting of foliage; 4) it should preserve soil structure; 5) water spreading should be accomplished without giving rise to injurious concentrations of soluble salts on or near the surface of the soil; and 6) it should require nothing more than cursory inspection and maintenance during the growing season.

In the last few years various watering devices have been manufactured and marketed. Growers have employed a number of these systems with a fair degree of success being reported by some. Others have found them unsatisfactory. Up to the present time no study has been undertaken to actually determine the relative merits of these systems. To set up a comparative study of all the systems on a scale large enough to lend itself to statistical treatment, would involve considerable expense and labor. Fortunately, the mode of water application and the principle involved in spreading the water throughout the entire soil mass permit these systems to be classified under one of five basic methods of irrigation.

With these considerations in mind, the problem has been set up in the manner outlined below.

Problem

Within practicable economic limits, which basic method of irrigation provides the most favorable soil-moisture-plant relations?

Problem analysis.—Before answering the major question, it is necessary to answer the following:

1. Which method of irrigation has the greatest beneficial effect on the growth of greenhouse carations?

2. Which method of irrigation requires the least number of water applications, or the longest time interval between irrigations?

3. Which method of irrigation has the most favorable effect on the keeping quality of cut flowers?

4. Which method of irrigation produces the least movement and accumulation of salts on or near the surface of the soil?

5. In which system is the least annual watering cost incurred?

Delimitations.--This study was limited to five basic methods of irrigating greenhouse carnations. These methods are considered basic in that, based on the mode of water application and the disposition of excess irrigation water, all greenhouse watering systems may be classified under one of them. These five basic methods are as follows:

1. Surface watering of benches with free-draining bottoms.

2. Subirrigation of benches with watertight sides and bottoms.

3. Surface watering of benches capable of storing two inches of free water.

4. Surface watering of benches capable of storing three inches of free water.

5. Maintaining a two-inch free water level in benches with watertight sides and bottoms by means of suitable valve and float mechanisms.

Surface watering could have been accomplished by using any one of several methods commonly used in the greenhouse but, in this study, hand watering with a garden hose was employed.

Subirrigation was accomplished by injecting water through short sections of one-half inch pipe inserted through the bottom of the bench. These pipes also served as drains for excess water.

Four hundred and twenty carnation plants of the White Sim variety, raised in 20 individual plots in the Research Greenhouses of Colorado A & M Experiment Station at Fort Collins, were used in this study.

Data on growth were obtained from flowers produced during the period October 4, 1954 to March 13, 1955. Irrigation records were kept between June 16, 1954, and March 17, 1955.

To determine the amount of soluble salts in the soil, specific conductance readings were taken on three 5:1 soil extracts prepared from samples obtained from each test plot at approximately three-month intervals.

Time and labor studies were conducted during the summer of 1953 at the Colorado A & M Research Greenhouses. The number of man-hours required to install some more common surface watering systems was observed during the fall and winter of 1954 and 1955.

Definition of terms--Growth in this study was measured by recording both the total production and quality of flowers produced.

Quality was determined on the basis of weight and stem length of cut flowers. The quality index, used in this study as an indirect measure of quality, is the weighted mean of the various grades of cut flowers. These grades were weighted as follows: five for fancy, four for standard, three for short, and two for split.

Free water as used in this study is water which would normally drain but which is kept from doing so by an impervious membrane bench lining. The water so stored is available for plant use.

Electrical conductivity is the reciprocal of the resistance in ohms of a conductor one centimeter long with a cross sectional area of one square centimeter. This is often referred to as specific conductance.

Chapter II

REVIEW OF LITERATURE

One of the greatest needs in the commercial production of greenhouse carnations has been a satisfactory watering system of reasonable cost. Such a system would have to add the proper amount of water to the soil with a minimum wetting of foliage, and without impairing the capacity of the soil to support plant growth. Since the success of any wateringsystem depends upon its ability to establish favorable soil-moisture-plant relations, a review of the various methods of watering would, of necessity, include some of the concepts of soil water, its movement in soil, the basic energy relationships in soil moisture problems, plant and moisture relations, and plant relations to saline and alkali soils.

The importance of keeping the foliage dry especially on cloudy days is recognized by carnation growers. As early as 1895, Taft (39) observed that moisture lodging in the axils of the lower leaves of plants promoted the development of parasitic fungi. A similar observation was made by Post (28), who emphasized the fact that prolonged periods of dampness on the lower leaves of plants create a condition favorable to the growth of leaf-borne diseases and to the activity of foliar nematodes.

The necessity of making moisture available to the plant at all times is a well recognized fact. It is essential to plant life in absorbing the plant food from the soil, in assimilating it, and in moving it to various parts of the plant. The moisture content in the soil at which the plant can perform its physical and chemical processes most efficiently is not well established. However, it is believed that there is a range somewhere between the wilting point and the moisture equivalent at which the moisture content is optimum. According to Israelson (17), this range lies between 55 to 100 per cent of the moisture equivalent, with an average of approximately 70 per cent. He claimed further that in very open soils this optimum is very nearly equal to the moisture equivalent, or, in terms of a more common soil moisture constant, to the field capacity. Since it is not always possible to hold the moisture content of the soil at the optimum value, Roe (35) has suggested that the ultimate theoretical aim in soil moisture regulation should be the maintenance of an adequate capillary supply. A better understanding of this may be gained by analyzing the soil moisture changes following irrigation. Edlefsen and Anderson (11) made the following observations on free-draining soils:

1. Immediately following or during irrigation, the soil moisture is raised to a point just below saturation. At this point the soil pores are largely filled and the soil contains its maximum moisture. Water in this condition is held very loosely and moves downward very rapidly under the pull of gravity, except where there is an impermeable layer which offers restraint to such movement.

2. As the loosely held moisture drains from the soil, a point is reached beyond which drainage ceases. The soil is then said to be at field capacity.

3. The plants will continue to reduce the water in the soil until finally the wilting point is reached. The moisture below the wilting point is held with such great force that it is unavailable to plants. The energy with which it is held in the soil increases very rapidly with but little additional loss of moisture.

Other investigators have described these soil moisture changes using slightly different terminology and have suggested a variety of classifications. Briggs (7) classified soil water as follows:

1. Hygroscopic water, which is adsorbed from the atmosphere as a result of attractive forces on the surface of the particles.

2. Capillary water, which is held by surface tension forces as a continuous film around the particles and in the capillary spaces.

3. Gravitational water, which drains under the influence of gravity.

Subsequent investigations by Briggs and his associates were concentrated on the analysis of capillary water in terms of the availability to the plant, especially from the standpoint of the optimum and minimum moisture contents for plant growth. Briggs and McLane (8) developed the soil moisture equivalent as a measure of the ability of the soil to hold water under a centrifugal force of 1000 times that of gravity. Later, Veihmeyer (42) showed this to be a fairly reliable measure of field capacity for fine-textured soils, but for coarse-textured soils, he found that the moisture equivalent is slightly lower than field capacity. Briggs and Shantz (9) then introduced the wilting coefficient as a measure of the moisture content of the soil at which plants permanently wilt.

The capillary water described by Briggs was later differentiated into three phases by Widtsoe and McLaughlin (43) who conducted experiments on the movement of water in irrigated soils. These phases are:

1. The maximum capillary-water capacity or the water content at capillary saturation against gravity.

2. The optimum capillary capacity in the moisture range most favorable for plant growth.

3. The lento-capillary point or the point where moisture movement is very slow.

These two investigators believed that root hairs could draw water from the soil at lower moisture contents only by being in direct contact with the moisture film.

Bouyoucos (3) made extensive studies on the freezing points of various phases of soil water and, on the basis of his findings, suggested a new classification which introduced the concept of unfree water, or water held so tightly to the colloidal particles that it is not readily frozen. He interpreted this as a sign that moisture held in this form would not be readily available to plants.

A modification of the Briggs classification which emphasized the importance of water vapor and film water in soils was suggested by Lebedeff (18). His classification may be summarized as follows:

1. Water vapor, which is controlled by vapor pressure equilibria. Movement takes place from higher to lower vapor pressures.

2. Hygroscopic water, in which the water molecules are held on the surface of particles by forces of adhesion. Movement occurs in the vapor phase from moist to dry areas.

3. Film water, which is under the influence of molecular forces of cohesion. Movement takes place in the liquid phase from thicker to thinner films.

4. Gravitational water, which moves under the influence of gravity.

Soil-moisture energy relationships

The concepts of soil water described thus far have all been based upon the capillary tube hypothesis, which considered the soil to be made up of numerous capillaries of varying dimensions. In this theory the ability of the soil to retain water was viewed to be a function of the tension of water films around particles. In 1907, a new theory for characterizing the soil moisture phenomena observed in soils, based on energy relationships, was evolved. This concept has gained wide acceptance and has gradually displaced the capillary tube hypothesis.

This new concept was initiated by Buckingham (10) who introduced the idea that flow of water through soil is comparable to the flow of heat through a metal bar, or to the flow of electricity through an electrical conductor. He thought of the driving force as the difference in attraction for water between two portions of the soil that are not equally moist. He suggested the term capillary potential as a measure of the attraction of the soil for water at any given point, and defined it as the work required to move a unit mass of water against capillary forces in a column of soil from a free water surface to a given point above this surface. He showed that the capillary potential depends upon the moisture content, θ, of the soil. He also developed a theoretical analysis for the relationship between the capillary potential and the distance from the water table. In his analysis, he assumed a soil of uniform packing in a state of equilibrium as far as moisture movement was concerned. He assumed further that evaporation did not take place at the surface of the soil mass. He then proceeded to show that

$$\psi = gX \qquad (1)$$

where ψ = capillary potential, $\left(\frac{FL}{M}\right)$;

X = distance of any given point above the free water surface, (L);

g = acceleration of gravity, $\left(\frac{L}{T^2}\right)$.

Buckingham thus established a relationship whereby, if the variation in moisture content with height is known, the relation of capillary potential to moisture content can be obtained. By plotting a series of curves of X against the moisture content θ, he showed that the force of attraction of the soil for water is a continuous function of soil moisture.

By expanding the original ideas of Buckingham, Gardner (13) was able to show that the capillary potential could be used to give a new interpretation to the various soil moisture constants employed by Briggs and others. His findings indicated that the capillary potential is a linear function of the reciprocal of the moisture content over a considerable range, and may be expressed by the relationship,

$$\psi = \frac{e}{\theta} + b \qquad (2)$$

where e and b are constants.

Richards (33) expanded the concepts of Gardner and developed a technique for hastening the attainment of equilibrium during capillary potential determinations. He used a 1/2-inch layer of soil on a porous plate sealed onto the top of a rectangular reservoir. He obtained various tensions by changing the amount of suction on the water in the reservoir. When the moisture content of the soil has attained equilibrium, the soil has a potential at that moisture content equal to the suction applied. The findings of Richards indicated that coarse-textured soils exhibit high potentials at low moisture contents, and that finer-textured soils contain more water at the same potential. He attributed this to the larger number of contacts in the finer-textured soils, thereby reducing the amount of moisture at each of the contact points. Later, Russell (36) supplied experimental evidence to corroborate the findings of Richards. In studying the tenacity with which moisture was held in four Iowa soils, he found that the higher the soil content of clay and silt in comparison with sand, the greater is the amount of water stored in the soil at equivalent tensions.

Subsequent investigations in the field of energy relationships associated with soil-moisture problems were concentrated on the technique of determining the capillary potential over a wide range of moisture contents. According to Baver (2), the more important methods developed were: 1) the vapor pressure method for extremely low moisture contents; 2) freezing-point depression and dilatometer methods for the moisture range most favorable for plant growth; 3) moisture absorption by seeds placed in contact with soils containing known amounts of water; 4) water distribution in long soil columns; and 5) water distribution under centrifugal force or under tension in porous clay cells or sorption blocks.

The most widely known method of measuring the capillary potential operates on a principle based upon the suction force of the soil for water. The first device designed to function under this principle consisted of a porous clay cup sealed onto a mercury manometer. The cup and part of the manometer is filled with water. The cup is placed in the soil and the system is allowed to attain equilibrium. A decrease in the moisture content of the soil allows water to leave the cup thereby causing the mercury in the manometer to rise. As the soil becomes wet, the tension of the water in the soil becomes less than that in the cup and water enters the cup, causing the mercury level in the manometer to drop. After some time a condition of equilibrium will be reached, and the potential of the soil at that moisture content is represented by the reading of the manometer. Gardner referred to this instrument as a capillary potentiometer. Later, Gardner and Richards (34) suggested the term tensiometer for the sake of brevity and to describe better the function of the apparatus. The fact that a tensiometer can operate over a limited range only, normally between field capacity and a tension of slightly less than one atmosphere, has not diminished its usefulness. Within this range, which is the most favorable for plant growth, it gives a quick measurement of the approximate amount of energy required to extract moisture from the soil. More recently, commercial tensiometers with small rubber balloons used in place of the mercury manometer have been developed. The suction exerted against the water in the cup is transmitted to the balloon, which in turn actuates a needle indicator calibrated to read the tension directly in some convenient unit.

The first attempt to simplify the concept of energy relations in soil-water problems was made by Schofield (37) in 1935. He hinted at the inadequacy of the term capillary potential to denote the energy with which water is held in the soil, since capillary or surface tension forces are only a part of the total forces involved in the attraction of water by soils. In its place he suggested the term pF which he defined as the logarithm of the height in centimeters of a column of water that is necessary to produce the required suction. The pF value theoretically includes all the energy restrictions on moisture in the soil at any given instant, and not the energy of cohesion and adhesion only. Using his experimental results and those of other investigators, and by using a logarithmic scale, Schofield was able to show the relationship between tension and moisture content on one graph. The curves he obtained showed that the soil moisture constants commonly used to characterize soil moisture relationships lie on the same curve. From these curves he deduced that the moisture content at field capacity corresponds to a pF value of about 2.7, and that permanent wilting takes place at a pF of about 4.2.

Osmotic effects of salts

It was stated earlier that surface tension forces are only a part of the total forces involved in the attraction of water by soils. It is believed that the ease of water absorption by plants is a function of the difference between the osmotic pressure of the plant root cells and the sum of the osmotic pressure of the soil solution and the tension exerted by the soil colloids. Magistad and Reitemeier (22) found that drastic fluctuations in the osmotic pressure of the soil solution greatly influence water availability. Working with plants in solution cultures, they found an almost inverse linear relationship between the osmotic pressure of the solution culture and the rate of plant growth. Magistad and his associates (21) obtained inverse linear relationships between salt concentration and the rate of growth of alfalfa. Similar relationships were reported to have been found for most crops tested. Several reasons have been given to account for this marked behavior, one of them being that, as the quantity of water is decreased by the growing plant, stresses on soil moisture resulting from increased concentration of salt in the soil solution increase much more rapidly over the available moisture range than the stresses owing to physical forces. It will be shown later that aside from reducing water uptake, salts have some direct effects on plant growth.

Movement of water

Since most of the devices employed in irrigating greenhouse benches rely upon the ability of the soil to move water vertically and laterally, a discussion of the basic principles of water movement in soils may prove valuable. This discussion will, however, be limited to the moisture range favorable for plant growth.

The movement of water through the soil pore space is brought about by the action of gravity or capillarity, or by a combination of both. In saturated soils the pore space is largely filled with water and the flow of water takes place in accordance with Darcy's law, which states that the velocity of flow of water through a column of soil is directly proportional to the difference in hydraulic head and inversely proportional to the length of the column. Expressed mathematically,

$$V = K \frac{h}{L} \qquad (3)$$

where V = velocity, cm/sec;

h = difference in hydraulic head, cm;

L = length of soil column, cm;

k = permeability coefficient, cm/sec.

The following expression which takes into consideration the viscosity of the fluid and a variable soil characteristic was developed by Slichter (38):

$$q = \frac{10.22\ pd^2S}{\mu hC} \qquad (4)$$

where q = quantity transmitted, cm/sec;

p = difference in pressure head, cm;

d = mean diameter of soil grains, cm;

S = cross-sectional area of soil column, sq cm;

h = height of soil column, cm;

μ = coefficient of viscosity of the fluid, poises;

C = a constant.

According to Baver (2), Zunker developed an expression for calculating the flow through a soil column which took into account a number of soil properties not considered in earlier formulae. This relationship is expressed as follows:

$$Q = \frac{\mu h}{LU^2N} \left(\frac{P_o}{1-P} \right) F \qquad (5)$$

where Q = quantity of transmitted water;

h = difference in pressure head;

N = coefficient of viscosity;

L = length of soil column;

U = effective specific surface;

μ = type and arrangement of the particles;

P = total pore space;

P_o = tension-free pore space;

F = cross-sectional area of the soil column.

The value of μ varies from 2.3 for round particles to 0.5 for disc-shaped particles, but is usually taken as 1.0 since most soils contain particles of various shapes. The tension-free pore space is calculated according to the formula,

$$P_o = P - \frac{w}{100}(1-P)S \qquad (6)$$

where w = inactive pore space occuring in 100 grams of dry soil;

s = specific gravity of the soil.

In unsaturated soils the larger pores are filled with air. Consequently, water movement is dependent upon a large number of air-water interfaces. The movement of water in unsaturated soils has been discussed from two viewpoints, namely: 1) the old concept of capillarity; and 2) the more recent analogies to the flow of heat or electricity. In the first concept, the soil is considered to be constituted of numerous capillaries of varying dimensions. If one of these capillary tubes is isolated, an expression for the theoretical height of capillary rise may be developed. Israelson (17) showed that the height of capillary rise may be calculated from the following expression:

$$h = \frac{2T}{rw} \qquad (7)$$

where h = height to which water willrise in the tube,

T = surface tension of water,

r = radius of capillary tube, and

w = specific weight of water.

In the centimeter-gram-second system, Eq. 7 reduces to

$$h = \frac{0.15}{r} \qquad (8)$$

The following values of the theoretical height to which capillary water will rise in different soils have been computed from Eq. 8, (2): fine gravel, 1/3 ft; coarse sand, 1.5 ft; fine sand, 7.5 ft; silt, 31.5 ft; fine silt, 150 ft; and clay, over 150 ft. Although some investigators have claimed that water has risen long distances from deep water tables, it is difficult to conceive that the distances shown above could be attained. Thorne and Peterson (40) claimed that in unsaturated soils the forces of cohesion between soil and water are so great that water movement is restricted. Alway and McDole (1) reported that upward movement of water from soil layers below 12 inches proceeds at a very slow rate after the moisture content drops below field capacity. They further claimed that water which penetrates beyond 16 to 20 inches does not return to the surface except by way of the plant roots once the moisture content has dropped below field capacity.

In connection with his studies on different subsurface watering devices, Post (28) observed that the capillarity of many greenhouse soils breaks at moisture tensions of two to three inches of mercury, and that watering devices which rely solely on capillarity for water spreading tend to leave some dry spots in the bench unless capillarity is reestablished. It is generally accepted now that in unsaturated soils, water will not move laterally more than a few centimeters toward plant roots in sufficient quantity to be of practical benefit to the plant.

In the case where movement of water takes place from a moist soil to a drier soil, Harris and Turpin (15) reported that the greatest rise or descent takes place where the initial moisture content of the source is greatest. They also observed that downward movement takes place at a faster rate than upward or lateral movement.

In the case of movement from a shallow water table to a dry soil, Moore (24) observed the following about the wetting front:

1. Water advances in a front from wet to drier soils under the influence of capillarity.

2. Beyond the front, the soil remains apparently dry, while immediately at and behind the front, the

soil is apparently completely wetted. There is a sharp line of demarcation between the obviously wet and dry soil.

3. The moisture content of the wetting front determined by sampling is constant, indicating a constant potential and constant radius of curvature.

The facts observed were interpreted as indicating that the difference in potential between the wetting front and the dry soil has little or no influence on the rate of movement of the front.

Movement of salts

Almost all the devices used in irrigating greenhouse benches rely to a certain extent on the capillary movement of water to achieve a uniformly moistened mass of soil. This is especially true of devices which inject water at relatively few points. A mode of application such as this favors the upward flow of soil solution to the surface. The salts carried by the water moving to the surface cannot be evaporated, hence, they are deposited on or near the surface. The concentration on the surface of salts which are normally distributed throughout the entire soil layer may cause serious salinity problems. The processes which lead to the formation of salted soils have been summarized by Magistad (20) as follows:

1. Salinization occurs when neither the surface nor ground waters drain away satisfactorily. Salt is concentrated by water evaporation. Sodium salts usually predominate in the early stages.

2. Alkalinization follows after equilibrium is established between the positively charged ions in solution and those adsorbed in the soil colloids. As sodium salts become more concentrated in the soil solution, greater quantities are adsorbed by the soil colloids and corresponding amounts of cations previously adsorbed are released. As the percentage of exchangeable sodium is increased, the soil becomes more alkaline in reaction.

Effects of salts on plants

The detrimental effects of salt concentration in soil are well recognized. It is also commonly accepted that some salts are more toxic than others, and that certain plants are able to tolerate high concentrations of salts while others are sensitive even to very low concentrations. The theory behind the observed toxicity of salts was built on the premise that salts in solution around plant roots reduced or prevented absorption of water by plants. This concept was widely accepted for some time, but the general applications of the concept, along with other effects of salt on plants and soils, were not extensively developed until the recent investigations at the U. S. Regional Salinity Laboratory were undertaken. Researchers at the U. S. Salinity Laboratory (41) found that saline soils, characterized only by the presence of excess salts in the soil solution, differ fundamentally from the alkali soils with high exchangeable sodium, poor physical condition, and frequent high alaklinity, in addition to varying amounts of soluble salts.

Plant relations to saline soils.—The principal salt ingredients of saline soils are formed by combinations of the following ions: Na, Ca, Mg, Cl, SO_4, HCO_3, and NO_3. The pH in most saline soils is not sufficiently high to injure most crop plants, and the level of exchangeable sodium is low. Thorne and Peterson (40) reported that the toxic effects of the salts in depressing plant growth may be attributed to one or more of three sources, namely: direct physical effects of the salts in preventing water uptake; direct chemical effects of the salts in disturbing the nutrition and metabolism of plants; and the indirect effects of salts in altering soil structure, permeability, and aeration.

The effect of salts on water uptake may be appreciated better by reviewing briefly the energy relations which exist in soil-moisture problems. It was pointed out earlier that the ease of water absorption by plants is a function of the difference between the osmotic pressure of the plant root cells and total soil moisture stress--the sum of the osmotic pressure of the soil solution and the tension exerted by the soil colloids. Meyer and Anderson (23) defined osmotic pressure as the pressure which must be exerted on a solution to prevent the passage of pure water into it through a semipermeable membrane. Thorne and Peterson (40) reported that as the quantity of water is decreased by the plants, stresses on soil moisture resulting from increased concentration of salts in the soil solution increase more rapidly over the available moisture range than the stresses due to physical forces. Magistad and Reitemeier (22) reported an almost inverse relationship between the rate of plant growth and the osmotic pressure of the solution cultures on which they were grown.

A disturbed plant metabolism caused by saline conditions has been viewed primarily in terms of nitrogen and carbohydrate relations. Nightingale and Farnham (25) observed that plant roots seem to lose their ability to assimilate nitrate nitrogen in solutions of high osmotic pressure. Long (19) also reported that absorption of nitrate nitrogen is reduced when appreciable quantities of sodium chloride are present in the soil solution. Other investigators have, however, found that at higher salt levels the accumulation of not only nitrate nitrogen but also of proteins and non-reducing sugars increased very markedly (40). These results have led them to believe that factors other than salinity have entered into some of the results. Conclusive proof is lacking that plant growth is affected adversely because of inadequate nitrogen absorption when growing on saline soils well supplied with available nitrogen. According to Thorne and Peterson (40), reduced photosynthesis from low moisture availability, as a result of osmotic effects, may be a more likely cause of reduced growth rather than nitrogen deficiency in saline soils well supplied with plamt nutrients.

The indirect effects of salts in soils become apparent after the excess salts are leached. Thorne and Peterson (40) contended that a large quantity of salts tend to keep the soil colloids in a good state of aggregation and desirable granular condition. As the excess salts are leached, however, the soil approaches an alkaline condition. Soils which have been high in sodium and are later leached, show an accumulation of adsorbed sodium ions on the clay particles. With the removal of excess salts some of the exchangeable sodium hydrolyzes, the soil pH is raised, the clay swells and becomes deflocculated, and drainage and aeration are impaired. Many saline soils are, therefore, probably as limited by poor aeration as by salt concentration in terms of normal crop production (40).

<u>Plant relations to alkali soils</u>.--Thorne and Peterson (40) reported that the adverse effects of alkali soils are brought about by a high caustic alkalinity, toxicity of the carbonate ion, and the effects of exchangeable sodium. They reported that a high caustic alkalinity has a direct effect on the plant roots and an indirect effect on the assimilation of certain plant nutrients. They observed that some plant roots and organic matter are dissolved when the soil pH exceeds 9.0. The results of their studies of field conditions in Utah led them to believe that a pH of about 8.8 should be adopted to distinguish conditions where alkalinity becomes toxic. Their results also indicated that soluble phosphate is assimilated less readily under alkaline conditions than under neutral or slightly acid conditions. Breazeale and McGeorge (6) have indicated that a root contact solution higher than pH 7.6 may impede nitrate absorption by plants although the pH is not sufficiently high to be directly toxic to plants. They found, however, that if the soil is well aerated, absorption of nitrates is not markedly retarded by pH values up to 8.0. In the field excellent growth of many crops had been obtained with pH values between 8.0 and 8.5 indicating that there had been no difficulty due to nitrogen nutrition.

An excess of exchangeable sodium exerts a two-fold effect. It promotes a poor physical condition in the soil and brings about an unbalanced nutrition in plants. Magistad and his associates (21) reported a progressive breakdown in soil structure and decrease in soil permeability and aeration with increasing exchangeable sodium percentage especially at values beyond 12 per cent. They observed that soils with high exchangeable sodium are deflocculated and puddled very readily even at comparatively low moisture contents.

Ratner (32) and Bower and Turk (5), working with artificially prepared soils, found that high exchangeable sodium limits plant growth by decreasing calcium uptake to the point that exchangeable sodium injury results more from calcium starvation than from direct sodium toxicity.

<u>Methods of irrigating carnation benches</u>

Based on the mode of water application, Post (28) has classified greenhouse watering methods as surface-watering methods, subsurface injection or subirrigation, and constant water level methods.

In Colorado, and possibly in the whole United States, surface watering by hand with a garden hose is still the most widely used method of applying water to greenhouse carnation benches. In the hands of an experienced waterer, uniform and thorough wetting of the soil can be attained with a minimum wetting of foliage. The drawbacks to its use, however, are the high cost of labor and the deterioration of the physical condition of the soil as a result of packing and washing away of surface soil. These have been minimized to a certain extent through the use of breakers attached to the discharge end of the hose. These attachments allow the injection of air into the water stream, thereby allowing relatively large volumes of water to discharge at much reduced impact.

The Skinner system of overhead irrigation has worked satisfactorily on field crops, but attempts to use it on greenhouse carnations have failed because of the undesirability of excessive foliage wetting. To adapt the Skinner system to carnation bench watering, Hasek (16) suggested that flat-spray nozzles which throw water in a semi-circle, placed not more than three to four inches above the soil, be used in place of the conventional nozzles. With but slight modifications, the 180-degree nozzles employed successfully today are essentially of the type proposed by Hasek.

A surface-watering device which utilizes the capillarity of the soil to accomplish thorough wetting of the entire soil mass was proposed by Post and Scripture (29) in 1947. To demonstrate the principle involved, they used copper tubes 1/2 inch in diameter, perforated with orifices 0.039 inch in diameter spaced 12 to 24 inches on centers. They covered the soil with a one-inch layer of fine sand, placed two tubes on the sand, and injected water into the tubes through a header located at the middle of the bench. The injection pressure was adjusted by means of a check valve, the desired pressure being that which just allowed water to rise four to eight inches vertically above the tube. Lateral movement of moisture was effected by capillarity, and in the presence of the layer of sand, it proceeded at a relatively rapid rate.

The latest efforts in connection with the adaptation of surface watering devices to carnation benches have been concentrated on the development of low-cost hose sprinklers designed to discharge as uniformly as possible through slits between the rows of plants. For this purpose plastic and rubber hoses of various shapes and designs have been manufactured. On account of the high friction loss in hoses of small diameter, a greater part of the head available at the source is lost in the first 20 or 30 feet of hose, with the result that when they are used on carnation benches, a very uneven water distribution results. Other problems commonly encountered in the use of hose sprinklers are the twisting of the hose and clogging of the slits. The first gives rise to difficulties in controlling the direction of the water streams discharging from the sides of the hose. Hose sprinklers of this type can be used to great advantage only if their hydraulic properties are such that 100-foot lengths or greater can be employed, and still overcome the inherent difficulties mentioned above.

Subirrigation consists of injecting water from the bottom of the bench and allowing it to rise through the soil. This method was used successfully in the field and in gardens before it was adopted for greenhouse use. One of the early attempts at greenhouse subirrigation was made by Green and Green (14) at the Ohio Experiment Station with the hope of preventing lettuce rot. The result on the growth of plants was so marked that it was repeated on a larger scale on various plants, with favorable results being reported. Later, applications of subirrigation to greenhouse production were made by Rane (31). Post (28) claimed the following desirable features about subirrigation: 1) it requires little time for the application; 2) thorough wetting of the soil is obtained; and 3) the whole process is accomplished with little or no wetting of foliage. He found, however, that for this system to work successfully, enough water should be injected to completely saturate the soil, the surplus being drained away. Later, he also found that the unidirectional flow of water to the surface and the subsequent evaporation of the portion not transpired by the plants results in the deposition of salts formerly carried in solution. To remedy this, he recommended that the bench be flooded and drained occasionally to leach out the excess salts and to redistribute the nutrients that have accumulated at or near the top.

A modification of the conventional method of subirrigation was recommended by Post and Seeley (30). They suggested the use of wicks spaced 18 inches apart, with their lower ends immersed in water contained in a trough suspended under the bench, and with their upper ends embedded in the soil. They reported that tests of this system on crysanthemums and stock plants yielded results comparable to those obtained from surface-watered benches, but that occasional surface watering was necessary. To date there is no published report that this method has been used successfully in carnation benches.

The constant level method evolved from the sub-surface injection method of subirrigating bench crops. In connection with this work, Post (26) found that roses grew as well or better when watered at a tension of one inch of mercury as compared to watering at three inches of tension. Encouraged by this result, he proceeded to make the system completely automatic by using watertight benches with "V" bottoms. Instead of injecting water intermittently, he maintained a constant level with a float valve set to discharge water when the level dropped below that desired. Subsequent tests of this method yielded results comparable to those previously obtained for water injection at tensions ranging from one to three inches of mercury. This method of watering keeps the soil moisture tension below one inch of mercury. The soil appears extremely moist but plant growth is apparently normal. As in the injection method, the upward flow of water and salts in solution results in the accumulation of salts on the surface. Here, however, the effects of excessive salt concentrations are less felt by the plants, since at low tensions, the water uptake is not appreciably reduced by the osmotic effects of salts. Post and Seeley (30) claimed that if the plants suffer from any adverse effects at all, they may be attributed more to lack of aeration or direct effects of salt on plant metabolism than to reduced water uptake.

Automatic watering devices

On account of the increasing cost of labor, efforts to develop automatic watering devices, or to make existing devices automatic, have been undertaken. All the automatic watering methods developed rely on capillarity to achieve the moistening of the entire soil mass. Post and his associates have been responsible for the development of a number of these devices. In an early work published by Post and Seeley (30), they reported that automatic watering may be accomplished by means of wicks, injection methods, constant level, and surface tube methods. Some of the desirable features they claimed for automatic watering are: 1) no wetting of foliage; 2) soil is not saturated but is kept uniformly moist; 3) there is no loss of fertilizer because there is no drainage water; 4) soil structure is not altered appreciably; 5) less water is required; and 6) the grower has better control of the amount of water applied and the moisture content of the soil. They observed that their automatic watering devices work well in soils that have good capillarity, and less satisfactorily in very loose soils with high organic matter content. They also reported that portions of the bench farthest from the source of moisture dried first, but that watering the entire bench when only the driest spots required water did not seem to produce any adverse effects on plant growth.

Attempts have been made to operate surface-watering devices automatically. This has been accomplished by connecting a tensiometer to a vacumn gage and wiring this through a relay to a solenoid valve. The flow of current is regulated by means of a time switch, which also regulates the length of time the valve is held open and the frequency of its opening. Openings at eight, twelve, and four o'clock are usually sufficient. The principle of operation is as follows: as the soil dries, the hand on the vacumn gage moves up until it touches the contact set at the maximum tension desired. The time switch allows the current to flow, thereby opening the valve. The valve is held open for a predetermined length of time, which is the length of time required to apply the desired amount of water at the given valve opening. The valve then closes, and when the time switch allows electric current to flow to the valve again, the gage hand has dropped from the contact, thereby breaking the circuit.

More recently, Bouyoucos (4) developed a new electric automatic irrigation system for greenhouse benches. The components of his device are a moisture measuring cell, a solenoid valve, and an electric controller. The moisture measuring unit is composed of nylon fabric with stainless steel electrodes. The nylon unit, when buried in the soil, becomes an integral part of the soil. It can absorb moisture from the soil and just as easily give it back to the soil, so that its moisture content tends to be in constant equilibrium with the soil moisture content. An indirect measurement of the moisture content of the soil is obtained by measuring the electrical resistance of the nylon unit, which varies with its moisture content. The nylon unit is highly sensitive and responds readily to changes in soil moisture in the moisture range most favorable for plant growth. The solenoid valve turns the water in the water line on and off electrically. The automatic controller is an electrical device which, by means of the solenoid valve, turns the water on and off as the need is indicated by the nylon unit. The scale of the meter is calibrated to read from zero to 100 per cent of the total available moisture content in any given soil.

A further advancement in the development of automatic watering devices was the incorporation of a timing system into the electric irrigation system proposed by Bouyoucos. This timing system allows the watering of a number of benches individually through a single controller. It consists of a stepping relay, a clock, solenoid valves, a controller, and nylon units. A nylon unit is buried in a representative spot in each bench. All the nylon units are then connected to the stepping relay, which is in turn connected to the controller. The hands of the clock make one revolution per minute, and as they revolve the proper electrical contacts are made, and the soil in each bench is tested as to its need for water. When a bench needs water, the clock disconnects itself and actuates the controller to turn on the water through the solenoid valve. The clock actuates the controller to turn off the water after the desired amount has been delivered. The hands of the clock then resume their revolving and testing.

Chapter III

METHODS AND MATERIALS

Hand watering with a garden hose is still the generally accepted method of applying irrigation water to carnation benches in Colorado. Its undesirable effects on soil structure and the high cost of watering incurred through its use have made this method unsatisfactory. To reduce the cost of watering, several labor-saving systems have been developed. On the basis of the mode of water application and the dispostion of excess irrigation water, these systems may be classified under one of the following basic methods of irrigation: 1) surface application of water on a free-draining bench; 2) subirrigation of a bench with watertight sides and bottoms; 3) surface application of water on a bench capable of storing two inches of free water; 4) surface application of water on a bench capable of storing three inches of free water; and 5) maintaining a depth of two inches of free water in a watertight bench by means of a suitable valve and float mechanism. These five basic methods of irrigation comprised the treatments in this investigation.

Preliminary studies

The reaction of bean plants to the five basic methods of irrigation was tested in unreplicated plots during the fall of 1953. One glass side in each plot was provided to facilitate the occasional examination of the plant root systems. Bean plants were used in the preliminary studies because they develop rapidly and send out extensive root systems in a relatively short period of time. On the assumption that the treatments which produce adverse effects on bean plants would most probably produce harmful effects on carnations, it was possible to determine in advance which treatments merited consideration in the final study.

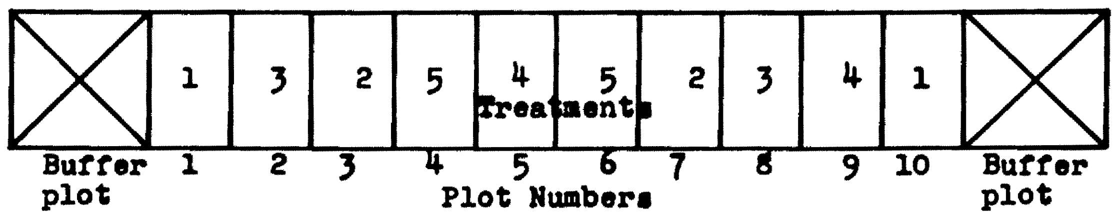
Irrigation studies on carnations

General procedures.--The basic methods of irrigation, numbered in the order they appear above, comprised the five different treatments in this investigation. A schematic diagram of the treatments showing the mode of water application and the disposition of excess irrigation water is presented in Fig. 3. Each treatment was replicated four times, making a total of 20 plots.

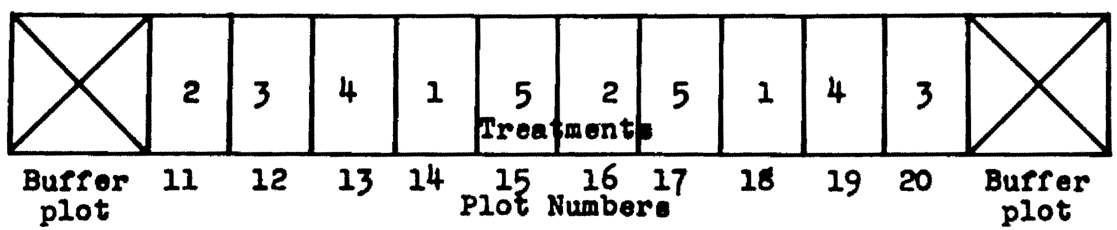
The test plots were constructed in two benches six inches deep, 40 inches wide, and 35 feet long. To minimize the variation in plant responses as a result of differences in location within a bench, the test plots

Fig. 1.-- Position of the 5 basic methods of irrigation in randomized block arrangement.

Location A



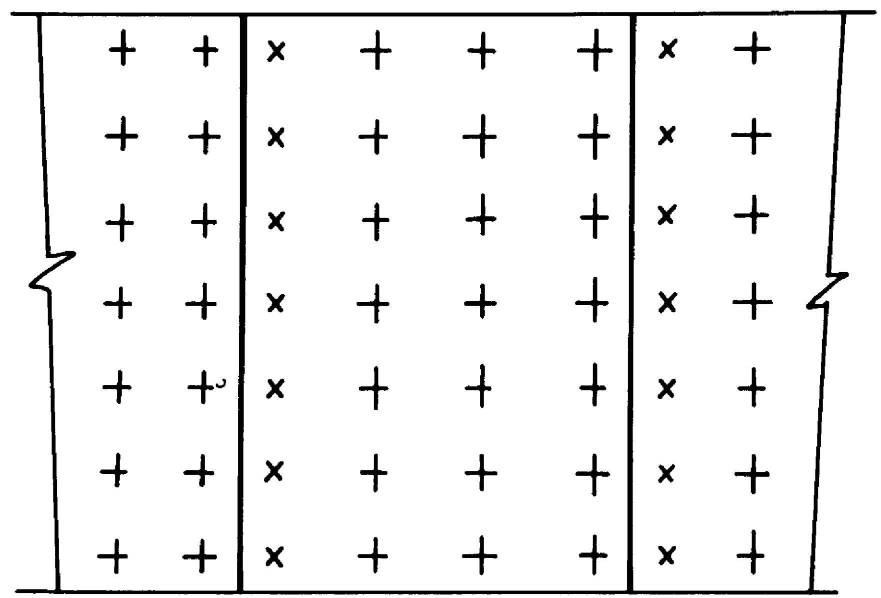
Location B



Buffer plots are 40" X 50"
Test plots are 32" X 40"

Treatment 1 -- Surface-watered, free draining.
Treatment 2 -- Subirrigated.
Treatment 3 -- Two inches of free-water temporarily stored.
Treatment 4 -- Three inches of free-water, temporarily stored.
Treatment 5 -- Free-water maintained at a constant depth of two inches.

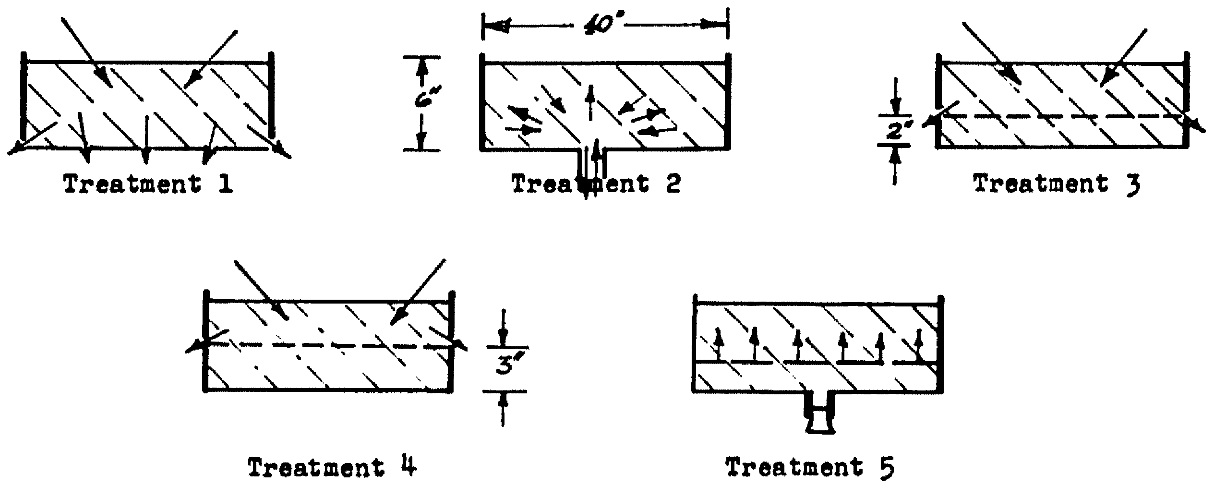
Fig. 2.-- Position of test plants and buffer plants in each test plot.



+ Test plants--White Sim

X Buffer plants--Gayety

Fig. 3. -- Schematic Diagram of Irrigation Treatments.



Treatment 1 -- Surface-watered, free draining.
Treatment 2 -- Subirrigated; drainage permitted after soil becomes saturated.
Treatment 3 -- Surface watered; provision made for 2 inches free water storage.
Treatment 4 -- Surface watered; provision made for 3 inches free water storage.
Treatment 5 -- Free water kept at a constant depth of 2 inches by means of a valve and float mechanism. Drainage permitted only when soil is leached.

were confined to that portion of the bench remaining after buffer plots 40 inches wide and 50 inches long have been constructed at both ends of the bench. Two replications of each treatment were assigned to each bench after dividing the space between the end plots into ten equal plots. This is shown in Fig. 1. Individual plots measured 32 by 40 inches.

With the exception of the plots of treatment 1, all the sides and bottoms of the test plots were lined with vinyl plastic to make them watertight.

A section of 1/2 inch pipe, 10 inches long, was inserted through the bottom of each of the plots of treatment 2 in such a manner that half of it was embedded in the soil and half of it was protruding beneath the bench. Water was injected into the bench through this pipe and, following irrigation, it also served as a drain for excess water.

Plots of treatment 3 were designed to store temporarily two inches of free water. This was accomplished by permitting excess water to drain only from side holes drilled two inches above the bottoms of the plots.

Plots of treatment 4 were designed to store temporarily three inches of free water. To accomplish this, excess water following irrigation was allowed to drain only from side holes drilled three inches above the bottoms of the plots.

On each of the four plots of treatment 5, a valve and float mechanism was installed for maintaining the water level in the plot at a depth of two inches. Drain holes were provided at the bottom of each plot in case a need for them arose.

After the installation of all the equipment necessary to insure the proper functioning of the plots in accordance with the desired treatments, the benches were steam sterilized.

Twenty-eight carnation cuttings consisting of 21 test plants of the White Sim variety and seven buffer plants of the Gayety variety were planted per test plot on June 15, 1954. The position of test and buffer plants within each plot is shown in Fig. 2. The row of buffer plants was included to eliminate the possibility of mixing flowers cut from any two adjacent plots. Following the firm establishment of each plant, the tops were pinched to promote lateral branching. With the exception of the method of water application and the subsequent disposition of excess irrigation water, the growing practices used in commercial greenhouse ranges were followed.

Growth records.--The records on growth consisted of notes on the general appearance of the plants as they responded to treatments, and of production records kept on test plants. The flowers were cut three times a week and were graded on the basis of weight and stem length. The variability resulting from height of cutting was minimized by cutting the flowers at the same level on any one cutting day. The weighted mean of the four grades of flowers cut was used as the criterion of quality. On the assumption that lower grades of flowers are less marketable in a competitive market, the weight scale adopted was as follows: five for fancy, four for standard, three for short, and two for split. The higher the value of the weighted mean, therefore, the better the quality that is indicated.

Irrigation records.—Records were kept on the number of irrigations required from June 15, 1954 to March 17, 1955. A mercury tensiometer was installed in each plot. With the exception of the plots of treatment 5, where the soil moisture tension was held at approximately one inch of mercury, all plots were irrigated when the tensiometers registered readings of nine to ten inches of mercury. Records were also kept of day to day soil moisture tensions within the interval created by two successive irrigations during both summer and winter. The tensiometers were read at nine o'clock every morning while this phase of the investigation was in progress to minimize the hourly variations resulting from vapor pressure changes in the soil. The data obtained showed the relative availability of moisture in the test plots.

Keeping studies.--Seven keeping trials were conducted during the winter of 1955. Five to seven flowers from each treatment were used per test. The keeping solution used was tap water with 100 ppm of chlorine added to inhibit the growth of decay-producing bacteria. The cut carnations were placed in a constant temperature room at $66^{\circ}F \pm 2^{\circ}$ and the mean number of days of useful life determined for each sample.

Specific conductance readings.--To ascertain the extent to which the five basic methods of irrigation promote the movement and accumulation of soluble salts on or near the surface of the soil, the top layer of soil in the test plots was carefully observed for salt incrustations. The salt toxicity in the soil was evaluated by measuring the conductance of three 5:1 extracts prepared from soil samples obtained from each plot at approximately three-month intervals. The specific conductance was measured by a Universal Solubridge, model RD-15, graduated to read in mhos X 10^{-5} per centimeter, and equipped with a micro dip-type cell, model Cel K-2. The 5:1 extract was prepared by adding 15 cc of distilled water to three grams of soil, shaking the sample for one minute, five times during a 1/2 hour period, and filtering through a Whatman No. 1 filter paper.

Extreme care was exercised to obtain representative samples of the soils contained in individuals plots.

This was accomplished by sampling the entire depth from at least two locations within each plot, intimately mixing the samples, and preparing the extract from a portion of the composite sample.

Annual cost of watering.--The cost estimates for the basic methods of irrigation tested are based on existing prices of materials and equipment. Capital needed to cover the initial cost of equipment and installation labor was assumed to be available at six per cent interest compounded annually. The annual fixed charge on investment and the operating expense comprised the annual cost of watering. The former was computed after establishing the initial cost and the expected life of the equipment. Equal annual payments were charged for installation. Labor spent in watering by the various methods comprised the major portion of the operating expense. The cost of routine inspection and maintenance was also charged to operation. All labor cost computations were based on a conservative figure of one dollar per man-hour.

An estimate of the annual cost of hand watering was made after studying the two-year irrigation records of nine carnation benches and establishing the time required to water a bench by hand. At the Research Greenhouse, the watering time varied with the available pressure head. The high and low values were used to obtain a range of possible watering costs.

Supplementary cost studies.--In addition to the cost figures computed for the methods tested in the randomized block experiment, the irrigation costs incurred through the use of some more common surface watering systems were estimated. These and figures supplied by the Dan Braun and the Cherry Creek Greenhouses of Denver were used to supplement the cost figures computed above.

Supplementary cost studies were made on the surface watering systems represented by the symbols SW-B, SW-C, SW-D, and SW-E in Table 5. These systems may be briefly described as follows:

1. SW-B, SW-C, and SW-D consist of staggered, 180-degree, flat-spray nozzles spaced 32 inches apart in 3/4 inch pipelines. The pipeline forms a closed loop along the sides and ends of the bench and may be supplied with water either at the middle or at one end of the bench. These systems differ only in the material used for the pipeline.

2. SW-E consists of two thin-walled pipes 1 1/2 inches in diameter. The pipes are laid longitudinally on the bench approxiiately six to ten inches from the sides. Water is supplied through a header at one end of the bench and discharged through small orifices spaced four inches apart along the sides of the pipes.

Statistical methods.--The irrigation study on carnations was arranged in four randomized blocks. The data on production and quality, frequency of irrigation, and cut flower life were analyzed by the analysis of variance.

Chapter IV
ANALYSIS OF DATA

The reaction of beans and carnations to five basic methods of irrigation, which comprised the treatments in this investigation, was tested. A schematic diagram of the treatments showing the mode of water application and the disposition of excess irrigation water is presented in Fig. 3.

Preliminary studies

The response of bean plants to the five irrigation treatments was tested in unreplicated plots during the fall of 1953.

Effect on root growth.--Observation of the plant root systems as they responded to irrigation treatments revealed that the most extensive root systems developed in treatment 1, where excess water drained freely, and in treatment 2, where the plot was subirrigated. Root growth extended to the bottom of the soil in these two treatments.

In treatments 3 and 4 where two and three inches of free water was temporarily stored, plant roots ceased to grow beyond the maximum level of free water. Closer examination of the root systems in these plots at the conclusion of the experiment revealed that the plants had sent out roots deeper into the soil as the free water level receded, but the roots were apparently killed by succeeding irrigations which restored free water to the original level. Extensive lateral root growths were observed in these plots.

In treatment 5 where free water was maintained at a constant depth of two inches, the roots stopped growing approximately 1/2 inch above the free water surface. However, very extensive lateral roots systems above the free water wurface were in evidence. The soil looked extremely moist and a white crust which developed gradually became very evident at the conclusion of the experiment.

Effect on plant growth.--Day-to-day observation of the general appearance of the plants showed that plants grown in treatment 5 produced longer but weaker growth accompanied by chlorosis of the plants. On three occasions the irrigation treatment was temporarily discontinued and free water in the plot was allowed to drain for three to five days. Each time the chlorotic condition of the plants disappeared, but chlorosis always reappeared three to four weeks after resuming the treatment.

The results of this investigation failed to show that any one treatment, with proper corrective measures, would be permanently injurious to plant growth. It was decided, therefore, that all the treatments merited consideration in the final study.

Irrigation studies on carnations

The response of carnations to five basic methods of irrigation was tested in four randomized blocks during the 1954-55 season. The quality and number of flowers produced, the frequency of irrigation, the useful life of cut flowers, the salt toxicity in the soil, and the estimated cost of watering were adopted as the criteria for the evaluation of the relative merits of the methods tested.

Effect on production and quality.--The results of the measurements made on the production and quality of flowers cut from individual plots are summarized in Table 1. The sample means shown are for four replications in each treatment. The results failed to show any real differences in the ability of the five basic methods of irrigation to promote production and enhance quality. The differences which occurred were due mainly to differences in location rather than to differences in treatment (Table A).

Effect on the frequency of irrigation.--The number of irrigations required by individual plots is

Table 1.--EFFECT OF FIVE BASIC METHODS OF IRRIGATION ON PRODUCTION AND QUALITY OF WHITE SIM CARNATIONS.

Treatment	Location	Plot number	Number of flowers				Quality index	Production per plot	Mean quality index	Mean production per plot
			Split	Short	Standard	Fancy				
1	A	1	0	4	48	67	4.53	119	4.37	135.00
		10	0	7	47	74	4.52	128		
	B	14	0	20	76	56	4.25	152		
		18	4	16	70	51	4.19	141		
2	A	3	0	4	43	50	4.47	97	4.38	130.00
		7	0	7	45	70	4.52	122		
	B	11	3	11	75	69	4.33	158		
		16	2	14	80	47	4.20	143		
3	A	2	0	9	57	52	4.36	118	4.38	138.25
		8	0	3	53	61	4.50	117		
	B	12	0	13	69	73	4.39	155		
		20	2	17	82	62	4.25	163		
4	A	5	0	6	52	50	4.41	108	4.35	130.25
		9	0	6	56	59	4.44	121		
	B	13	0	12	98	52	4.25	162		
		19	0	16	61	53	4.28	130		
5	A	4	1	4	46	52	4.45	103	4.33	115.25
		6	2	13	50	49	4.28	114		
	B	15	1	13	68	49	4.26	131		
		17	1	8	58	46	4.32	113		
L.S.D. at 5 per cent level									NS	NS
L.S.D. at 1 per cent level									NS	NS

presented in Table 2. Also shown are the number of water applications in each treatment expressed as a percentage of the number of applications required in treatment 1. The sample means shown are for four replications in each treatment. The differences resulting from differences in treatment were real enough to be significant at the one per cent level. Differences in location also produced significant differences in the frequency of irrigation (Table B). Treatments 2, 3, and 4 definitely required fewer water applications as compared to treatment.1.. Treatment 2 required fewer applications than treatment 3, but there was essentially no difference between treatments 2 and 4.

The results of the soil moisture tension measurements from day to day following irrigation are plotted in Figs. 4 and 5. Fig. 4 shows the relative availability of moisture during summer within the interval created by two successive irrigations, whereas, Fig. 5 was drawn for one such interval during winter.

Effect on keeping quality of cut flowers.—The results of the flower keeping tests are summarized in Table 3. The sample means shown are for seven keeping trials in each treatment. The differences in the life of cut flowers resulting from treatment differences were great enough to be significant at the one per cent level.

Table 2.— EFFECT OF FIVE BASIC METHODS OF IRRIGATION ON THE FREQUENCY OF IRRIGATION.

Treatment	Location	Plot number	Number of water applications	Mean number of water applications	Number of applications expressed as a percentage of that of treatment 1
1	A	1	49	52.0	100
		10	47		
	B	14	56		
		18	56		
2	A	3	26	27.25	52.4
		7	24		
	B	11	32		
		16	27		
3	A	2	31	32.75	62.98
		8	26		
	B	12	39		
		20	35		
4	A	5	29	30.0	57.69
		9	27		
	B	13	32		
		19	32		
	A	4	Kept constantly moist by means of valve and float mechanism	--	--
		6			
	B	15			
		17			
L. S. D. at 5 per cent level				3.61	
L. S. D. at 1 per cent level				5.25	

Fig. 4.-- Relative availability of water.
(Summer)

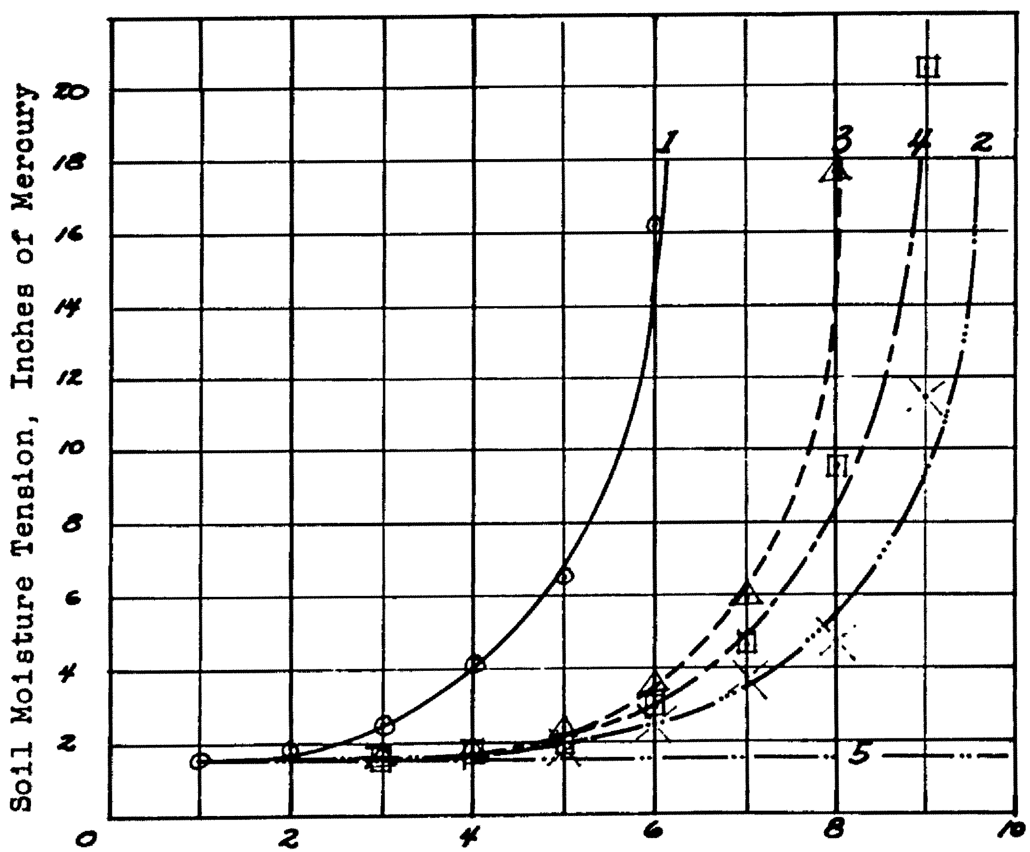


Fig. 5.-- Relative availability of water.
(Winter)

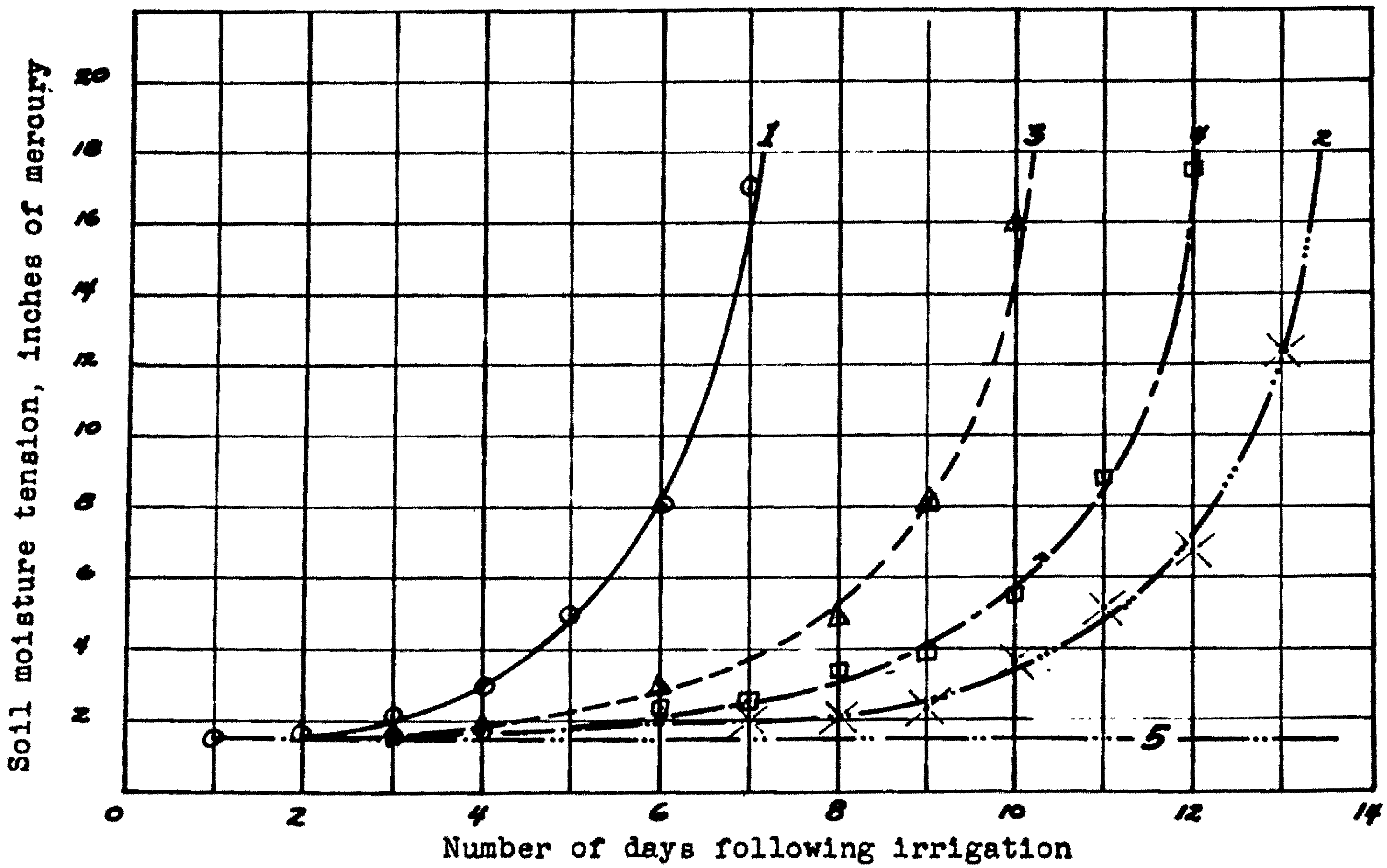


Table 3.—EFFECT OF FIVE BASIC METHODS OF IRRIGATION ON THE KEEPING QUALITY OF WHITE SIM CARNATIONS.

Trial number	Mean life in days — Treatment 1	2	3	4	5	L.S.D. at 5 per cent level	L.S.D. at 1 per cent level
1	7.83	8.33	8.17	8.83	6.83		
2	9.60	10.60	10.28	10.40	9.00		
3	9.17	11.00	9.83	12.14	9.17		
4	10.83	11.50	11.50	11.67	11.33		
5	9.50	10.75	10.00	9.50	9.50		
6	8.00	8.00	8.83	9.50	7.50		
7	7.86	9.29	8.29	8.86	8.43		
Mean life per treatment	8.97	9.92	9.56	10.13	8.82	0.58	0.79

Treatments 2, 3, and 4 yielded flowers of better keeping quality than treatments 1 and 5. There were no significant differences between treatments 1 and 5 and between 2, 3, and 4.

Effect on the accumulation of salts.--The results of the specific conductance measurements on 5:1 extracts prepared from three samples obtained from each plot at approximately three-month intervals are presented in Table 4. The specific conductances shown in column 4, treatment 5, were obtained after each plot had been leached twice. The results showed that salt accumulation was greatest in treatment 5 and least in treatment 1. Intermediate concentrations were observed in treatments 2, 3, and 4. Occasional inspection of the soil surfaces showed the gradual formation of a salt crust on each of the plots of treatment 5. A few white spots, much thinner and less pronounced than those observed in treatment 5, were also in evidence in treatment 2.

Annual cost of watering.--An estimate of the annual cost of watering incurred through the use of the basic methods tested in the randomized block experiment was made. In addition supplementary irrigation cost studies were made on some more common surface watering systems tested individually during the past year. Cost figures supplied by the Dan Braun and the Cherry Creek

Table 4.--EFFECT OF FIVE BASIC METHODS OF IRRIGATION ON THE ACCUMULATION OF SOLUBLE SALTS.

Treatment	Plot number	Specific conductance (mho x 10^{-5}) Sampling date Aug. 7, '54	Nov. 5, '54	Feb. 11, '55	Mean conductance per treatment
1	1	36	26	30	30.33
	10	42	30	28	
	14	38	26	24	
	18	32	24	28	
2	3	58	64	70	55.17
	7	40	55	54	
	11	56	64	58	
	16	48	40	55	
3	2	55	68	76	60.50
	8	62	70	82	
	12	58	55	64	
	20	32	46	58	
4	5	36	45	58	47.50
	9	30	48	62	
	13	42	44	68	
	19	38	44	55	
5	4	100	88*	110	86.50
	6	96	82*	90	
	15	70	66*	85	
	17	82	74*	95	

*Specific conductance determined after leaching twice.

Greenhouses of Denver were used to supplement the results of the studies at Fort Collins. The combined results are summarized in Table 5. The results showed that compared to hand watering, all systems which employ some mechanical means of applying water are less expensive to install, maintain, and operate. A break-down of the annual repayment costs or fixed charges on investment and installation labor is presented in Table 6.

Table 5.---ANNUAL REPAYMENT COSTS, OPERATING EXPENSES, AND TOTAL WATERING COSTS FOR SOME CARNATION WATERING SYSTEMS.

Treatment	Watering system	Type of system	Repayment costs for materials and installation	Cents per foot per year Labor	Total watering expense
(1)	(2)	(3)	(4)	(5)	(6)
1	SW-A	---	---	33-49.4	33-49.4
	SW-B	H-P	11.18	5.75	16.93
	SW-C	H-P	10.00	5.75	15.75
	SW-D	H-P	7.71	5.75	13.46
	SW-E	L-P	7.05	7.25	14.30
2	S-1	L-P	12.24	3.10	15.34
	S-2	L-P	11.19	3.10	14.29
3	SW-A	---	10.20	21-31	31.2-41.2
	SW-B	H-P	21.38	3.67	25.05
	SW-C	H-P	20.20	3.67	23.87
	SW-D	H-P	17.91	3.67	21.58
	SW-E	L-P	17.25	5.17	22.42
4	SW-A	---	10.20	19-28.5	29.2-38.7
	SW-B	H-P	21.38	3.33	24.71
	SW-C	H-P	20.20	3.33	23.53
	SW-D	H-P	17.91	3.33	21.24
	SW-E	L-P	16.74	4.83	21.57
5	Constant level	L-P	10.68	5.71	16.39

SW-A Handwatering with garden hose
SW-B 180° nozzles and 3/4" Gates flexible hose sprinkler system
SW-C 180° nozzles and 3/4" California flexible hose sprinkler system
SW-D 180° nozzles and 3/4" galvanized pipe sprinkler system
SW-E Greco hose sprinkler system
S-1 Subsurface injection with flexible hose pipeline and injection pipes
S-2 Subsurface injection with galvanized pipeline and injection pipes
H-P High pressure system
L-P Low pressure system

Table 6.--BREAKDOWN OF REPAYMENT COSTS FOR MATERIALS AND INSTALLATION SHOWN IN TABLE 5.

Treatment	Watering system	Item	Initial cost (cents/ft)	Expected life (years)	Annual charge (cents/ft)
(1)	(2)	(3)	(4)	(5)	(6)
	SW-B	Gates flexible hose plus installation cost	52	5	11.18
	SW-C	California flexible hose plus installation cost	44.8	5	10.00
1	SW-D	3/4" galvanized pipe and fittings	32.0	20	2.64
		180° nozzles	13.9	10	
		Installation cost	25.6		5.07
		Total			7.71
	SW-E	Hose and header	18.5	3	
		Installation cost	1.5		7.05
2	S-1	3/4" flexible hose and 1/2 x 10" injection pipes	11.00	5	
		Installation cost	3.33		3.22
		1/2" tees, nipples, etc.	9.00	20	
		Installation cost	3.33		1.02
		Vinyl plastic lining	11.20	2	
		Installation cost	4.40		8.00
		Total			12.24

Table 6.---BREAKDOWN OF REPAYMENT COSTS FOR MATERIALS AND INSTALLATION SHOWN IN TABLE 5.---(continued)

Treatment	Watering system	Item	Initial cost (cents/ft)	Expected life (years)	Annual charge (cents/ft)
(1)	(2)	(3)	(4)	(5)	(6)
2	S-2	1/2 x 10" injection pipes	2.00	5	
		Installation cost	3.33		1.19
		1/2" galvanized pipe, tees, and nipples	21.00	20	
		Installation cost	3.33		2.00
		Vinyl plastic lining	11.20	2	
		Installation	4.40		8.00
		Total			11.19
3	SW-A	Vinyl plastic lining	11.20	2	
		Installation cost	8.60		10.2
	SW-B	Gates flexible hose plus installation cost	52.0	5	11.18
		Vinyl plastic lining	11.20	2	
		Installation cost	8.60		10.20
		Total			21.38
	SW-C	California flexible hose plus installation cost	44.80	5	10.00
		Vinyl plastic lining plus installation cost	19.80	2	10.20
		Total			20.20

Table 6.--BREAKDOWN OF REPAYMENT COSTS FOR MATERIALS AND INSTALLATION SHOWN IN TABLE 5.--(continued)

Treatment	Watering system	Item	Initial cost (cents/ft)	Expected life (years)	Annual charge (cents/ft)
(1)	(2)	(3)	(4)	(5)	(6)
3	SW-D	3/4" galvanized pipe and fittings	32	20	2.64
		180° nozzles and installation cost	39.5	10	5.07
		Vinyl plastic lining and installation cost	19.8	2	10.20
		Total			17.91
	SW-E	Hose, header and installation cost	20.00	3	7.05
		Vinyl plastic lining and installation cost	19.80	2	10.20
		Total			17.25
4	Same as treatment 3	Same as treatment 3	Same as 3		Same as 3
5	Constant water level	Float valve, copper tubing, fittings, installation cost	20.90	10	2.68
		Plastic lining and installation cost	15.60	2	8.00
		Total			10.68

Chapter V

DISCUSSION

A number of labor-saving watering systems have been manufactured and marketed within the last ten years. Carnation growers have employed a number of these systems with a fair degree of success being reported by some. Others have found them unsatisfactory. This investigation was undertaken to show the relative merits of these systems and to establish their suitability in watering carnations. Consideration of all watering systems in an investigation extensive enough to be analyzed statistically would entail considerable expense and effort. Fortunately the mode of water application and the subsequent disposition of excess irrigation water permit the classification of nearly all greenhouse watering systems under one of five basic methods of irrigation. These five basic methods, which comprised the irrigation treatments in this investigation, are shown in Fig. 3.

Preliminary Studies

Root growth

The results of preliminary studies on the reaction of bean plants to the basic methods of irrigation indicated that free water temporarily stored in the soil inhibits root growth beyond the maximum free water level. There was some evidence to show that the plants sent out roots deeper into the soil as the free water surface receded, but the roots were apparently killed by succeeding irrigations which restored free water to the original level. Free water maintained at a constant level in the soil produced similar results on root growth. This study further showed that conditions which check root growth in the downward direction encourage extensive lateral root growth. The reduction in the depth of root growth owing to the presence of free water did not seem to have any adverse effects on plant growth. Apparently the additional lateral growth was sufficient to offset the possible ill effects of reduced growth in the downward direction.

Plant growth

Observation of the plants in treatment 5 showed that keeping the growing medium at a soil moisture tension of approximately one inch of mercury results in longer but weaker growth accompanied by chlorosis of the plants. The improvement of the general appearance of the plants following drainage and their tendency to revert to the chlorotic condition three to four weeks after the resumption of the irrigation treatment showed that something connected with lack of soil air was responsible for the chlorosis. Except for the chlorosis of the plants in treatment 5, the irrigation treatments seemed to produce no visible effects on plant growth.

Irrigation Studies on Carnations

Plant growth

Chlorosis.—Similar results were observed with carnations as were observed with beans in the preliminary test. Plants in treatment 5 eventually became chlorotic. Plants in treatment 4 exhibited this condition to a lesser extent. There was no indication that production and quality were impaired in either case.

Location.—The differences in quality and production were due mainly to differences in location. Plots in location B consistently produced more flowers than those in location A, but their quality indices were lower. Bench B was located south of bench A and was adjacent to a bench which was vacant periodically. The increased light received by bench B was held responsible for the increase in production.

Frequency of irrigation

The results of studies on the effect of the irrigation treatments on irrigation frequency indicated that free water stored temporarily in the soil prolongs the time interval between irrigations. Water that would normally drain is prevented from doing so and is rendered available for plant use. The results of this study further indicated that when water injected in excess of the water-holding capacity of the soil is allowed to completely saturate the soil before being permitted to drain, a similar effect on the time interval between irrigations is produced. This arises from the fact that free-draining soils seldom attain complete saturation. Israelson (17) reported that free-draining soils retain as much as 15 per cent of the air in the voids following irrigation. By ponding excess water in the plot for as long as six hours, as was done in treatment 2, nearly all the air in the voids is expelled. The additional water so provided prolongs the time interval between irrigations. The temporary lack of soil air did not produce adverse effects on quality, production, and the useful life of cut flowers.

<u>Keeping quality</u>

The five basic methods of irrigation definitely affected the keeping quality of cut flowers. Treatments 1 and 5 which yielded flowers with the shortest useful life represent the two extreme conditions of moisture availability. The growing medium is kept at a low moisture tension in treatment 5, whereas, treatment 1 holds the soil moisture content at field capacity for only relatively short periods of time. Apparently extremely moist conditions in the growing medium impair the keeping quality of cut flowers although there is no apparent effect on production. The same is probably true of relatively dry growing media where soil moisture stresses increase very rapidly from day to day. Intermediate conditions of moisture availability produced a variable effect on the life of cut flowers. The treatment which had the longest interval between water applications did not necessarily produce flowers of the best keeping quality. Apparently factors other than moisture availability affect cut flower life.

Salt movement and accumulation

The specific conductance measurements on 5:1 extracts prepared from three soil samples taken from each plot at approximately three-month intervals showed that plots of treatment 5 consistently yielded much higher conductivity readings, indicating that salts were accumulating faster in these plots than in others. The gradual formation of a salt crust on each of these plots further revealed that redistribution of salts which have found their way to the surface was not taking place. This behavior was attributed to the mode of water application employed in these plots. When water is continually supplied from the bottom unidirectional flow of water from the bottom to the surface takes place. In rising to the surface, the water carries some dissolved salts which are deposited on or near the surface as the water is evaporated. Since the plots are not surface-watered, redistribution of the salts does not take place, and since the plots are not permitted to drain, the possibility of carrying away some of the excess salts in the drainage water does not exist. In this investigation, two leachings over a three-month period proved effective in reducing the salt content of the soil. These findings corroborated the observations made by Post (28) on greenhouse benches watered by the constant level method. The high salt levels observed in these plots produced no adverse effects on production and quality. However, it is probable that without leaching, injurious salt concentrations could develop within the space of one growing season.

The results of this investigation also indicated that surface application of water in quantities great enough to be slightly in excess of the water-holding capacity of the soil keeps salt content at a relatively low value. It was further indicated that the greater the number of water applications required, the lower is the specific conductance. The soil is usually subjected to some leaching with each water application.

In treatment 2, where water is injected from the bottom, rises, and spreads laterally as in treatment 5, the failure of salts to accumulate at a rate comparable to that observed in treatment 5 requires some explanation. Instead of adding just enough water to moisten the soil, as is customarily done, water was supplied in quantities slightly in excess of the water-holding capacity. The excess water proved effective in removing some of the excess salts.

Annual cost of watering

The combined results of the estimates of the watering costs incurred through the use of the basic methods of irrigation tested in the randomized block experiment and some more common surface watering systems showed that, compared to hand watering, all systems which employ some mechanical means of applying water are less expensive to install, maintain, and operate. The reduction in the cost of labor more than offsets the high initial investment in surface watering and subsurface injection equipment. The slight reduction in the number of water applications in treatments 3 and 4 does not justify the added expense of installing the vinyl plastic lining.

The last column of Table 5 shows a number of watering systems which differ in total watering cost by no more than a few cents per linear foot of bench space. The practical significance of such findings lies in the possibility of selecting from a number of high and low pressure systems one which will function best under conditions existing within a commercial range.

Selection of Watering System

The results of this investigation failed to reveal a method of irrigation which provides the most favorable soil-moisture-plant relations as measured by the criteria mentioned earlier. In spite of the many advantages which may be claimed for each of the watering systems, there is not a single system which does not have some shortcomings, either from the operational standpoint or from its effects on plant growth and other related factors. The investigation did show, however, that with proper corrective measures, a number of watering systems can be satisfactorily employed at reasonable cost.

The choice of a satisfactory watering system will be influenced by the length of benches and the pump capacity or pressure head at the water main. For a given pump capacity, a number of low pressure systems can be turned on simultaneously without affecting the evenness of water distribution, whereas, the same number of high pressure systems turned on simultaneously would probably produce such great drops in pressure head that uneven water distribution would result.

Convenience and ease of operation also merit consideration in the choice of a watering system. On this basis the constant level method of treatment 5 would be desirable because very little labor is required. However the problems associated with this method may give rise to operational difficulties.

The subsurface injection system of treatment 2 presented no major problems either from the operational standpoint or growth of carnations. Extensive lateral branching was observed in plants watered by this system and although the first-year production was not significantly different from other treatments, some real differences in its favor might show up in the second-year crop.

The surface watering systems SW-B, SW-C, SW-D, and SW-E can be installed at reasonable cost and have been found to function efficiently. SW-E has on occasion presented some difficulties. It was observed that the system becomes ineffective when the soil becomes extremely dry because water will not move more than a few centimeters in sufficient quantity to satisfy the water-holding capacity of the soil. Dry spots form and the drier they are allowed to get, the more ineffective the system becomes. In cases such as this it was found necessary to surface-water the bench and succeeding irrigations were made at soil moisture contents wetter than normal to attain more rapid lateral water movement. The effects of frequent, light waterings are not well established, and unless they can be shown to produce a significant increase in production, the added watering cost may not be justified.

Suggestions for Further Study

In the course of this investigation, it became evident that some aspects which seem to warrant further investigation have been overlooked. These are:

1. The effects of frequent light waterings on the production, quality, and keeping quality of carnations, and on the cost of watering.

2. The salt content of the soil at which the resulting toxicity begins to produce adverse effects on the growth and productivity of carnations in soils watered at soil moisture tensions of nine to ten inches of mercury.

3. An extended comparative study of surface-watering and sub-surface injection systems to determine if some significant differences in production and quality will show up in the second-year crop.

Chapter VI

SUMMARY

The response of greenhouse carnations to five basic methods of irrigation was tested during the 1954-55 season. Desirability of the methods tested has been viewed primarily in terms of the promotion of favorable soil-moisture-plant relationships within practicable economic limits. The quality and number of flowers produced, the frequency of irrigation, the useful life of cut flowers, the salt toxicity in the soil, and the estimated cost of watering were adopted as the criteria for the evaluation of the relative merits of the methods tested.

The productivity of carnations and the quality of flowers produced were not affected by the basic methods of irrigation.

The basic methods of irrigation produced very significant differences on the frequency of irrigation. Surface-watered, free-draining benches required the greatest number of water applications. Free water stored temporarily in the soil lengthened the time interval between irrigations by as much as 3 to 5 days. Soil-moisture tension measurements revealed that, compared to free-draining plots, those provided with temporary free water storage remained at field capacity for relatively longer periods of time. The time interval between irrigations in plots watered by the injection method was essentially the same as those observed in plots supplied with three inches of free water.

The basic methods of irrigation definitely affected the keeping quality of the flowers produced. The results indicated that flowers cut from plants grown in soils kept in a nearly constant state of saturation, and those cut from plants grown in relatively dry soils, where soil moisture stresses increase rather rapidly from day to day, did not keep as well as the flowers cut from plants raised under intermediate conditions of moisture availability. The differences in the mean useful life of cut flowers resulting from differences in the method of irrigation ranged from 1/2 to 1 1/4 days.

The mode of application of irrigation water produced a variable effect on the movement and accumulation of salts in the soil. In plots where water was injected from the bottom at relatively few points, the salt content of the soil increased gradually, except where water supplied in excess of the normal water-holding capacity of the soil was permitted to drain. The results of specific conductance measurements indicated that the salt content of the soil in plots which were surface-watered remained at a relatively low value. Frequent water applications proved effective in preventing the development of excessive concentrations of salts.

Estimates of the annual costs of watering showed that considerable savings can be effected by eliminating hand-watering methods. All the watering systems which employ some mechanical means of injecting water into the soil or of spreading it on the surface proved less expensive to install, maintain, and operate. A number of these low-cost systems differ in total watering cost by only a few cents.

The results of this investigation failed to reveal a basic method of irrigation which provides the most favorable soil-moisture-plant relations as measured by the five criteria mentioned earlier. In spite of the many advantages that may be claimed for each of the watering systems, there is not a single system which does not have some shortcomings, either from the operational standpoint or from its effects on plant growth and other related factors. This investigation did show, however, that with proper corrective measures, a number of watering systems can be employed satisfactorily at a reasonable cost.

A P P E N D I X

APPENDIX LIST OF TABLES

Table A.--TABLE OF VARIANCE FOR TOTAL PRODUCTION.

Source of variation	D.F.	Sum of squares	Mean squares	F-value Observed	F-value 5% level
Treatment	4	1,241.50	310.38	2.25	3.48
Location	1	4,530.05	4,530.05	32.89**	4.96
Treatment x location	4	576.70	144.18	1.05	3.48
Error	10	1,377.50	137.75		
Total	19	7,725.75			

Table B.--TABLE OF VARIANCE FOR QUALITY OF CUT FLOWERS.

Source of variation	D.F.	Sum of squares	Mean squares	F-value Observed	F-value 5% level
Treatment	4	0.0080	0.0020	0.42	3.48
Location	1	0.1567	0.1567	32.65**	4.96
Treatment x location	4	0.0357	0.0089	1.85	3.48
Error	10	0.0477	0.0048		
Total	19	0.2481			

Table C.--TABLE OF VARIANCE FOR NUMBER OF IRRIGATIONS REQUIRED.

Source of variation	D.F.	Sum of squares	Mean squares	F-value Observed	5% level
Treatment	3[a]	1,512.51	504.17	103.31**	4.07
Location	1	156.25	156.25	32.02**	5.32
Treatment x location	3	16.24	5.41	1.11	4.07
Error	8	39.00	4.88		
Total	15	1,724.00			

[a] Treatment 5 was not considered in this analysis.

Table D.--TABLE OF VARIANCE FOR MEAN LIFE OF CUT FLOWERS.

Source of variation	D.F.	Sum of squares	Mean squares	F-value Observed	5% level
Treatment	4	9.20	2.30	8.21**	2.65
Replications[a]	6	44.22	7.37		
Error	24	6.72	0.28		
Total	34	60.14			

[a] The effect of location was not considered in this analysis.

B I B L I O G R A P H Y

BIBLIOGRAPHY

1. Alway, F. J. and McDole, G. R. Relation of the water retaining capacity of a soil to its hygroscopic coefficient. Journal of Agricultural Research, 9:27-71, April 9, 1917.

2. Baver, L. D. Soil physics. New York, John Wiley and Sons, 1948. 398 p.

3. Bouyoucos, G. L. A new classification of soil moisture. Soil Science, 11:33-48, January 1921.

4. Bouyoucos, G. L. A new electric automatic irrigation system. Agronomy Journal, 44:448-451, August 1952.

5. Bower, C. A. and Turk, L. M. Calcium and magnesium deficiencies in alkali soils. American Society of Agronomy. Journal, 38:723-727, August 1946.

6. Breazeale, J. F. and McGeorge, W. T. Nutritional disorders in alkaline soils as caused by deficiency of carbon dioxide. Arizona. Agricultural Experiment Station. Technical bulletin, 41:113-153, 1941.

7. Briggs, L. J. The mechanics of soil moisture. U. S. Bureau of Soils. Bulletin, 10:1-24, 1897.

8. Briggs, L. J. and McLane, J. W. The moisture equivalent of soils. U. S. Bureau of Soils. Bulletin, 45:1-23, 1907.

9. Briggs, L. J. and Shantz, H. L. The wilting coefficient for different plants and its indirect determination. U. S. Bureau of Plant Industry. Bulletin, 230:56-73, 1912.

BIBLIOGRAPHY.--Continued

10. Buckingham, E. Studies on the movement of soil moisture. U. S. Bureau of Soils. Bulletin, 38:1-61, 1907.

11. Edlefsen, N. E. and Anderson, A. B. Thermodynamics of soil moisture. Hilgardia, 15:1-298, February 1943.

12. Fossum, M. T. Floricultural and ornamental horticultural economics. Chicago, Society of American Florists and Ornamental Horticulturists, 1950. 150 p.

13. Gardner, W. The capillary potential and its relation to soil moisture constants. Soil Science, 10:357-359, November 1920.

14. Green, W. C. and Green, E. C. Subirrigation in the greenhouse. Ohio. Agricultural Experiment Station. Bulletin, 61:57-76, 1895.

15. Harris, F. S. and Turpin, H. W. Movement and distribution of moisture in the soil. Journal of Agricultural Research, 10:113-155, July 16, 1917.

16. Hasek, R. New overhead watering method developed for the greenhouse. Florida. Agricultural Experiment Station. Bulletin, 108:1-19, 1947

17. Israelson, O. W. Irrigation principles and practices. New York, John Wiley and Sons, 1950. 405p.

18. Lebedeff, A. F. The movement of ground and soil waters. International Congress of Soil Science. Proceedings, 1:1:459-494, 1927.

19. Long, E. M. The effect of salt additions to the substrate on intake of water and nutrients by roots of approach-grafted tomato plants. American Journal of Botany, 30:594-601, October 1943.

20. Magistad, O. C. Plant growth relations in saline and alkali soils. Botanical Review, 11:181-230, April 1945.

BIBLIOGRAPHY.--Continued

21. Magistad, O. C., Ayers, A. D., Wadleigh, C. H., and Gauch, H. G. Effect of salt concentration, kind of salt, and climate on plant growth in sand cultures. Plant Physiology, 18:151-166, April 1943.

22. Magistad, O. C. and Reitemeier, R. F. Soil solution concentrations at the wilting point and their correlation with plant growth. Soil Science, 53:351-360, May 1943.

23. Meyer, B. S. and Anderson, D. B. Plant Physiology, New York, D. Van Nostrand, 1939. 696p.

24. Moore, R. E. Water conduction from shallow water tables. Hilgardia, 12:383-426, March 1939.

25. Nightingale, G. T. and Farnham, R. B. Effects of nutrient concentration on anatomy, metabolism, and bud abscission of sweet pea. Botanical Gazette, 97:477-517, March 1936.

26. Post, K. Automatic watering of roses, 1943-1946. American Society for Horticultural Science. Proceedings, 49:33-36, 1947.

27. Post, K. The constant level versus surface watering for roses. American Society for Horticultural Science. Proceedings, 49:441-443, 1947.

28. Post, K. Florist crop production and marketing. New York, Orange Judd Publishing Company, 1949. 891p.

29. Post, K. and Scripture, P. F. Copper tube surface automatic watering. American Society for Horticultural Science. Proceedings, 49:395-404, 1947.

30. Post, K. and Seeley, J. G. Automatic watering for greenhouse crops. New York. (Ithaca). Agricultural Experiment Station. Bulletin, 793:1-26, 1943.

BIBLIOGRAPHY.--Continued

31. Rane, W. F. Subirrigation in the greenhouse. West Virginia. Agricultural Experiment Station. Bulletin, 33:250-270, 1893.

32. Ratner, E. I. The influence of exchangeable sodium in the soil on its properties as a medium for plant growth. Soil Science, 40:459-471, December 1935.

33. Richards, L. A. The usefulness of capillary potential to soil moisture and plant investigations. Journal of Agricultural Research, 37:719-742, December 15, 1928.

34. Richards, L. A. and Gardner, W. Tensiometers for measuring the capillary tension of soil water. American Society of Agronomy. Journal, 28: 352-358, May 1936.

35. Roe, H. B. Moisture requirements in agriculture. New York, McGraw Hill Book Company, 1950. 413p.

36. Russell, M. B. Soil moisture sorption curves for four Iowa soils. Soil Science Society of America. Proceedings, 4:51-54, 1939.

37. Schofield, R. K. The pF of the water in soil. International Congress of Soil Science. Transactions, 3:2:37-48, 1935.

38. Slichter, C. S. Theoretical investigation of the motion of ground waters. U. S. Geological Survey. Annual Report, 19:pt.2:295-315, 1898.

39. Taft, L. R. Irrigation for the garden and greenhouse. U. S. Department of Agriculture. Yearbook, 1895:233-246.

40. Thorne, D. W. and Peterson, H. B. Irrigated soils, their fertility and management. Philadelphia, The Blakiston Company, 1949. 288p.

BIBLIOGRAPHY.--Continued

41. U. S. Regional Salinity Laboratory. Diagnosis and improvement of saline and alkali soils. Riverside, California, 1947. 157p.

42. Veihmeyer, F. H. and Hendrickson, A. H. The moisture equivalent as a measure of the field capacity of soils. Soil Science, 32:181-193, September 1951.

43. Widtsoe, J. A. and McLaughlin, W. W. The movement of water in irrigated soils. Utah. Agricultural Experiment Station. Bulletin, 115:195-268, 1912.