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THESIS

SPRINKLER SYSTEM LAYOUT DESIGN ALGORITHMS AND SOFTWARE INTERFACE

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A Thesis Submitted in Partial Fulfillment of
the Requirements for the Degree of
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The main objective this research was solid-set sprinkler layout software developmentin which the USUKU model was developed with a GIS interface (as a Mapwindow Plug-in) for integrating water application uniformity calculations, a pipe hydraulic model, and irrigation sprinkler pipe system layout.

The two main objectives of the water application uniformity module used for USUKU: (1) existing projects by evaluating water application uniformity; and, (2) for designing a new sprinkler system by evaluating the expected water application uniformity as calculated from a hydraulic analysis. Both evaluation results can be presented in a water application map, and characterized as a water application uniformity coefficient.

The pipe hydraulic module for USUKU is branching hydraulic model based on a gravity-fed concept and was specifically developed for sprinkler and trickle irrigation. The golden section search method was applied in the model. The Dijkstra algorithm is used to create flow paths from the water source to all nodes. The flow accumulation can be created by duplicate path links.

The irrigation sprinkler pipe system layout module is a pipe layout editor. This is used to create pipe layout data for the hydraulic module and water application module. The results of the hydraulic module and water application module are used to evaluate and select alternative pipe layouts for a given topography and field shape.

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Student's signature Thesis Advisor's signature

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Kasem Pinthong
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LIST OF ABBREVIATIONS

R = wetted radius

P = operating pressure (kPa)

q = discharge or flow rate (cms)

d = pipe diameter

dn = nozzle diameter

Kd = the nozzle coefficient

H = the sprinkler pressure head (m)

i = the water application rate (mm/h)

a = the area covered by each sprinkler

Z_{iq} = the average of the lowest one-quarter of the measured values

Z_{av} = the average infiltrated depth in the entire field

DU = distribution uniformity (%)

CU = coefficient of uniformity (%)

Z = the individual depths (mm) of catch observations from uniformity test

m = the mean depth (mm) of the observations

P_n = the minimum sprinkler pressure (kPa)

P_a = the average sprinkler pressure (kPa)

e_a = application efficiency

Z_r = the average depth of water added to the root zone storage (mm)

D = the average depth of water applied to the field (mm).

SWD = being the soil water deficit (mm)

AELQ = application efficiency of the low quarter

PELQ = potential efficiency of the low quarter

$Z_{lq,MAD}$ = the average low quarter depth infiltrated (mm) when equal to MAD;

D_{MAD} = the average depth of water applied when SWD = MAD

MAD = the management allowed deficit (mm)

LIST OF ABBREVIATIONS (Continued)

D_e = Discharge Efficiency (%)

$Z_{observed}$ = the average water depth (mm) observed at the ground surface

$Z_{discharged}$ = the average water depth discharged (mm)

DE_{pa} = the distribution efficiency for the desired percentage adequacy

R_e = the effective portion of water applied, after estimating the losses by evaporation and wind drift

O_e = the effective portion of water discharged after estimating thelosses by leakage

SPRINKLER SYSTEM LAYOUT DESIGN ALGORITHMS AND SOFTWARE INTERFACE

INTRODUCTION

1. Background

At present, irrigated areas support agricultural production for a growing world population, as well as a source of alternative energy in the form of biofuels. Thus, the importance of irrigated agriculture is greater than ever. However, many areas of the world are not appropriate for open-channel gravity-flow irrigation due to topography and water resource limitations. In these areas, an alternative is to use pressurized irrigation methods, which are often more expensive than surface irrigation methods.

The focus of this research is the development of design algorithms for fixed (solid-set) sprinkler systems. One way to approach the design ofsolid-set agricultural sprinkler systems is to develop software to handle many of the tasks, including iterative calculations. However, many different algorithms are required to implement such software and toobtain solutions that meet sprinkler irrigation design requirements. The research presented herein addresses these design challengers.

2. Problem Statement

A sprinkler irrigation system layout consists of the following components: supply source location, mainline, laterals, and sprinklers. A sprinkler irrigation system layout also depends on field (planted area) shape and topography. The parameters to make a decision for selecting a sprinkler irrigation system layout that conforms to a given topography are pressure distribution and water application uniformity. The layouts can be enormous, and it can be difficult to develop designs that are consistent with various conditions and restrictions, especially for irrigation design decision support for solid-set sprinklers or drip emitter. To develop such a system, a set of algorithms is required to assist an irrigation system designer in step-by-step decision making, leading to one or more design alternatives.

The main goal of this research was to develop software containing with algorithms which are useful for sprinkler system layout design. In this research, a prototype was developed to integrateseveral algorithms and a graphical user interface (GUI) as a design tool for solid-set sprinkler and drip irrigation systems.

OBJECTIVES

The main objective of the present work was to develop a sprinkler system design model leading to the following outcomes:

1. To analyze sprinkler and drip system layout design by considering three main sub-topics:
   (a) The required parameters;
   (b) Algorithms, tools, apparatus, and methods; and,
   (c) A user-friendly graphical interface.
2. To study different aspects of algorithms that areappropriate for application to sprinkler and drip system layout design.
3. To develop software for sprinkler system layout design by considering three main sub-topics:
   (a) Graphical user interface for integrating the data into a GIS environment, allowing graphical analysis of the network under different conditions;
   (b) Application of the algorithm and the development of the code for hydraulic computations and water application uniformity; and,
   (c) The development of a reporting capability, such as results in tabular format, in graphical format, and through maps.
4. To develop software for solid-set sprinkler and drip system layout design according to various parameters.

LITERATURE REVIEW

Irrigation systems analysis is the process of determining the water application performance and defining the system requirements necessary to meet system design standards for pressure and/or discharge (Lamaddalena and Sagardoy 2000). Network analysis can be used to determine the adequacy an existing irrigation system, to identify the causes of its deficiencies, and to develop cost-effective improvements. Network analysis can be also used for improving design techniques.

1. Sprinkler Irrigation Project Design

An irrigation system should meet the objectives of productivity which will be attained through the optimization of investment and operating costs. A number of parameters must be specified to design the system (Figure 1.). These may be classified into environmental parameters and decision parameters. The environmental parameters cannot be modified and must be taken into account as data for the design area. The latter depend on the designer decisions. The most important environmental parameters are:

- Climatic conditions;
- Soil or pedologic conditions;
- Cropping patterns;
- Socio- economic conditions of farmers; and,
- Type and location of the water supply.

Information on the climatic conditions is required for the computation of crop reference evapotranspiration. Rainfall is important for the evaluation of a supplementary water volume that may be utilized by crops without the need for irrigation. Information on the pedologic conditions of the area under study is important to identify the boundaries of the irrigation scheme, the percentage of uncultivated land, the infiltration characteristics of the soil and the related irrigation parameters (infiltration rate, field capacity, and others).

The available water resources usually represent the limiting factor for an irrigation system. In fact, the available water volume, especially during the peak-use period, is often lower than the water demand and storage reservoirs are needed in order to satisfy, (fully or partially) the demand. Also, the location of the water resource with respect to the irrigation scheme must be taken into account because it may lead to expensive conveyance pipes and or high head losses.

Finally, the socio-economic conditions of farmers must be taken into account. They are important both for selecting the most appropriate delivery schedule and the most appropriate on-farm irrigation method. All the above parameters have a great influence on the choice of the possible cropping pattern. The most important decision parameters are:

1. Cropping pattern;
2. Satisfaction of crop water requirements (partially or fully);
3. On-farm irrigation method;
4. Density capacity of hydrants;
5. Discharge of hydrants; and,
6. Water delivery schedule.

The cropping pattern is based on climate data, soil water characteristics, water quality, market conditions and the technical level of farmers. The theoretical crop water requirement is derived from the cropping pattern and the climatic conditions. It is important to establish, through statistical analysis, the frequency that the crop water requirement will be met according to the climatic conditions. Usually, the requirement should be satisfied in four out of five years (80% of the time). The requirements must be adjusted by the overall efficiency of the irrigation system. The computed water volume must be compared with the available water volume to decide the irrigation area and/or the total or partial satisfaction of the crop waterrequirements.

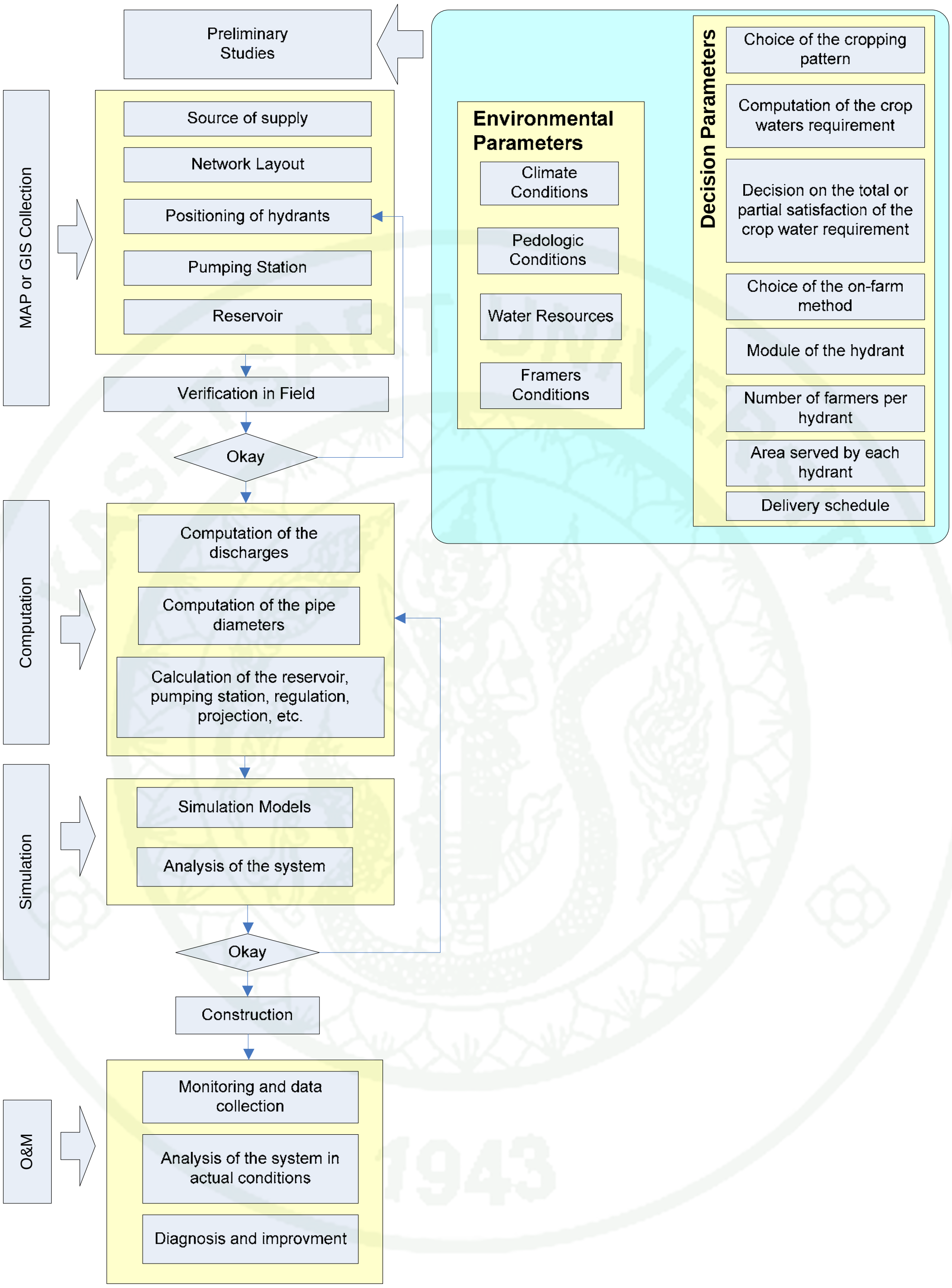


Figure 1 Schematic of the main activities in a sprinkler irrigation project from design to operation

2. Sprinkler Characteristics

A. Types of Sprinkler System

Sprinkler irrigation systems can be broadly divided into set systems and continuous-move systems. In set systems, the sprinklers remain at a fixed position while irrigating, whereas, in continuous move systems, the sprinklers operate while moving in either a circular or a straight path. The set systems include systems moved between irrigations, such as hand-move and wheel line laterals, hose-fed sprinkler grid, perforated pipe, orchard sprinklers and gun sprinklers. These are referred to as periodic-move systems. Set systems also include such systems as solid-set sprinklers, which are referred to as fixed systems. The principal continuous-move systems are center pivot and linear moving laterals, and traveling sprinklers.

With carefully designed periodic-move and fixed systems, water can be applied uniformly at a rate based on the intake rate of the soil, thereby preventing runoff and damage to land and to crops. Continuous-move systems can have even higher uniformity of application than periodic-move and fixed systems. Also,the travel speed of these systems can be adjusted to apply light watering that reduce or eliminate runoff (Keller and Bliesner 2000).

1. General Sprinkler Characteristics

Every sprinkler is characterized by:

- The operating pressure (*P*), required to provide the best water distribution;
- The discharge or flow rate (*q*) corresponding to a given pressure *P*; and,
- The diameter (*d*) of the wetted circle or the throw (*R*) corresponding to each pair (*P*, *q*).
- R is wetted radius ($R = K_r H^x$) (1)

The same sprinkler may be utilized for different combinations of P and q, depending upon the nozzle diameter (d_n). Therefore, the sprinkler charts given by the manufacturer should provide information on the best combination (H, q, d) for each value of d_n. The characteristics H-q-d are related as follows:

$$q = K_d H^{0.5} \tag{2}$$

Where:

K_d isthe nozzle coefficient

H is the sprinkler pressure head (m); and,

The parameters K_d and K_r primarily depend on the nozzle diameter, but they also vary with the design and manufacturing of sprinklers (Perreira 2003).

2. Factors Affecting Water Application

The rate at which sprinklers apply water when operating is called the application rate. It is given by:

$$i = \frac{q*1000}{a} \tag{3}$$

Where:

i is the water application rate (mm/h); and,

a is the area covered by each sprinkler.

The process of water application in set sprinkler systems depends on the following factors (Tarjuelo 1995):

The sprinkler water distribution pattern depends on: (1) the sprinkler design, nozzle characteristics (size, type, and number), and the working pressure; (2)the sprinkler layout,referring to the rectangular or triangular shape and the spacing between sprinklers; and (3)wind speed and direction. This is the major factor distorting the sprinkler pattern, and it plays an important role with regard to evaporation and drift losses.

B. Sprinkler Water Distribution Pattern

1. Sprinkler Design

Rapid rotation of a sprinkler may considerably affect the break-up of the stream. A jet of water in the air tends to carry with it an envelope of air moving at a velocity approaching that of the jet. When the condition is achieved, air drag on the jet is at a minimum. If the jet is made to change position, it encounters a new mass of air that may be essentially at rest, thereby providing resistance to the water. A rapidly rotating sprinkler is affected by wind more than sprinklers with lower rotation speeds (Solomon 1990).

The trajectory angle of the sprinkler (the angle above horizontal at which the water jet leaves the sprinkler) can influence the water pattern, and hence application uniformity. In the absence of air drag, a 45° trajectory would give the maximum wetted diameter for a given nozzle and pressure. Due to the air resistance encountered by the water jet, the trajectory angle for maximum throw is actually less, perhaps just over 30°. In the presence of wind, however, high trajectory angles suffer the disadvantage that the water is in the air longer, and hence more susceptible to the wind. For sprinklers to be used in moderate to high wind conditions, lower trajectory angles are available for use in higher wind conditions (Solomon 1990).

2. Nozzle Characteristics

At a given pressure, relatively large drops are obtained from large nozzles and fine sprays from small ones. For that reason, all manufacturers recommend operating pressures or ranges of pressures that will result in the most desirable application pattern for each combination of sprinkler and nozzle size and sprinkler spacing. Smaller sized nozzles produce a greater number of small drops because a smaller diameter receives air at the core of the jet sooner. Kincaid et al. (1996), agreeing with results obtained by Kohl (1974), showed that the effect of the nozzle size is smaller than the pressure effect.

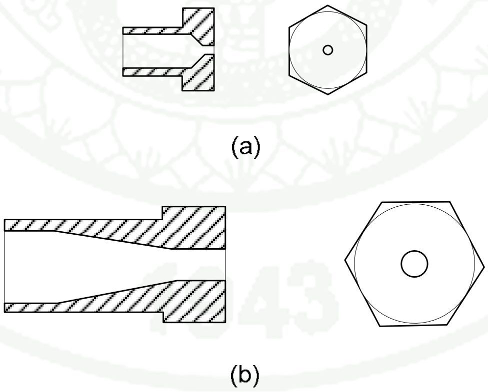
For a given pressure, increasing the nozzle size will increase both sprinkler flow rate and wetted diameter, but flow rate will increase considerably more than diameter. Increasing the nozzle size generally means an increased application rate as well.

The internal design of a sprinkler main nozzle is divided into three parts:

a) The first cylindrical part at the inlet, typically of about 5 mm in length and 10 mm diameter;

b) cylindrical part at the outlet of about 5 mm in length and different diameters depending on the amount of water to be discharged; and,

c) An intermediate tronco-conic part, which links both cylindrical parts, with the corresponding length to complete the total 20-mm length of the nozzle.



(a)

(b)

Figure 1 Nozzle internal design

When VP (straightening vanes) are not used, the first cylindrical part may not exist. In this case the tronco-conic part is longer and the convergence angle is smaller. Tarjuelo et al. (1999) verified that these factors were beneficial as they lead to slightly longer water distribution radial profiles, resulting in a positive effect on irrigation uniformity. If the final cylindrical part is shortened, reducing it up to a 3 mm length, for example, the water radial distribution patterns become shorter, since a larger interweaving of streamline is produced, thus breaking the jet earlier.

The VP equally decreases distortion by wind making the jet more compact and achieving a farther throw. It been shown that when using the VP for a wind speed higher than 2 m/s, better CU are obtained (Tarjuelo et al. 1992); otherwise, VP will cause a reduction in the CU.

Number of nozzles: Water from the spreader nozzle is usually much finer and more diffuse than the spray from the main nozzle, so it is much more affected by the wind. Using the largest possible main nozzle will tend to maximize wetted diameter and minimize wind distortion. Thus, unless the wind conditions are unusually calm, a single nozzle sprinkler will generally have the better coverage, the higher uniformity and the superior resistance to the wind (Solomon, 1990).

Tarjuelo et al. (1999) showed that higher irrigation uniformity was achieved, in radial indoor tests, when the sprinkler works with a double nozzle than when it does with a single nozzle. When the sprinkler was fitted with a VP or was located at two meters height, a farther throw was attained.

3. Working Pressure

In selecting nozzle sizes and operating pressures for a required sprinkler discharge, the designer should know that different pressures affect the profile as follows:

At the lower side of the specified pressure range for any nozzle, much of the water remains in relatively large drops. When pressure falls too low, the water from the nozzle concentrates in a ring a distance away from the sprinkler, giving a poor precipitation profile (Figure 3 A). On the high side of the pressure range, the water from the nozzle breaks up into relatively fine drops and settles around the sprinkler.

Under such conditions, the profile is easily distorted by wind movement (Figure 3 B). Within the desirable range, the sprinkler should produce a precipitation profile similar to Figure 3 C. (Keller and Bleisner 2000).

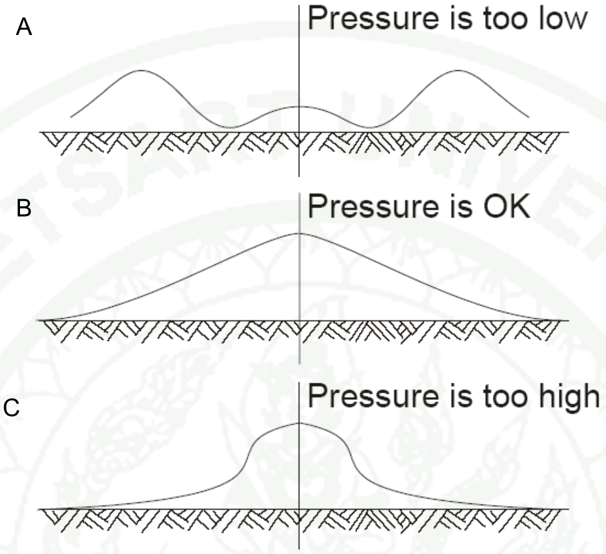


Figure 2 Relative effects of different pressures on precipitation profiles for a typical double nozzle sprinkler (after Merkley 2009)

In a great number of sprinkler nozzles an anomalous phenomenon was found, which has been called “turbulence”. This phenomenon can be explained as follows:

When exceeding a specific working pressure, the streamlines are distorted inside the main nozzles, so that discharge decreased considerably between 5 and 10% of initial discharge. The radius of throw is also lowered by about 0.8 m (5% of the value without turbulence). Consequently, the main effect of turbulence was the discharge depletion (Tarjuelo et al. 1999). An approximate method of checking pressure is to observe the shape of water jet. If the line of the jet is straight, the sprinkler is working at the correct pressure. If it is bow-shaped, the pressure is too low (Perreira 2003).

4. Pressure Regulators

The function of pressure regulators is to maintain approximately a constant downstream pressure. Pressure regulators cause a pressure loss and are useful when the upstream pressure is too high, but they cannot increase the pressure. A pressure regulator can be dynamic (work when only the water is circulating) or static (if they are hermetically closed when the water is not flowing).

There are different types of pressure regulators, but the most widely used in sprinkler irrigation is the spring type (Tarjuelo, 1995). For maintaining good pressure uniformity between the sprinklers on a given lateral, it is necessary to use a pressure regulator at the all inlet of laterals, or in some of them.

There is a kind of sprinkler nozzle where the flow is held relatively constant even when pressure fluctuates over a limited range. Such a nozzle has an elastomer washer that controls the size of the orifice. When no pressure is present, the washer is in a natural and relaxed state. As system pressure increases, radial deformation occurs, contracting the elastomer washer and narrowing the orifice. The orifice size is proportionally reduced according to the pressure applied. As a result, the flow is held approximately constant even when the pressure fluctuates.

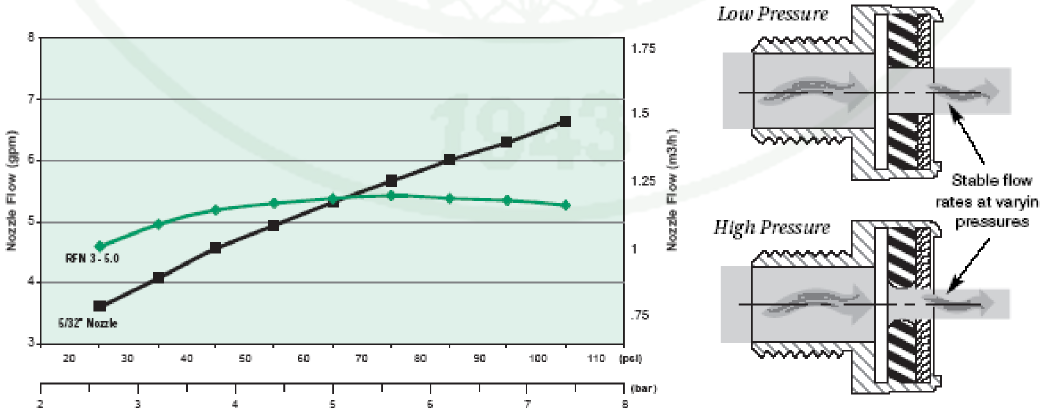


Figure 3 Flow limiter nozzle designs (Rainbird 2002).

C. Sprinkler Layout

The depth of the water applied to an area surrounding a revolving sprinkler varies with the distance from the sprinkler. Thus, to obtain a reasonably high degree of uniformity of application, water from adjacent sprinklers must be added (Figure 5).

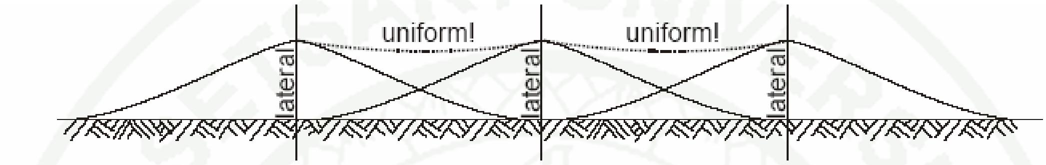
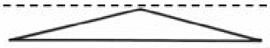
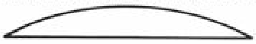
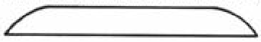
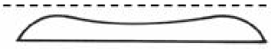


Figure 5 Overlapping example of sprinkler water profile (Merkley and Allen, 2006).

Some studies recommend triangular sprinkler spacing while others show no clear advantages between these and rectangular shapes, but it depends affects the sprinkler water distribution pattern (Keller and Bleisner 2000; Tarjuelo et al. 1992).The wetted diameter as well as the precipitation profile is of great importance in deciding the sprinkler spacing and the system design. Stylized profiles (Christiansen 1942) are shown in Table 1, along with spacing recommendations based on the diameter of effective coverage under low-wind conditions.

Table 1 Christiansen's geometrical application rate profiles and optimum set sprinkler spacing as a percentage of the effective wetted diameter

SPRINKLER PROFILE		RECOMMENDED SPACING AS A PERCENTAGE OF DIAMETER		
TYPE	SHAPE	SQUARE	TRIANGULAR EQUILATERAL	RECTANGULAR SHORT x LONG
A		50	50	40 x 60 to 65
B		55	66	40 x 60
C		60	65	40 x 60 to 65
D		40 70 (FAIR)	70 to 75	40 x 70 to 75
E		40 80 (FAIR)	80	40 x 80

In general a triangular shape (type A and B) corresponds to the combinations of two nozzles, the rectangular shape (Type C and D) to the combinations with one nozzle without VP, and the donut shape (Type E) to the combinations with one nozzle and VP (Tarjuelo et al. 1999) and it is generally produced with gun sprinklers or sprinklers operating at pressures lower than those recommended for the nozzle size (Keller and Bliesner 2000).

D. Sprinkler Irrigation System Performance

Two terms which describe the performance of sprinkler irrigation system are the uniformity and application efficiency. These two terms are related since a high uniformity is required to attain a satisfactory level of irrigation efficiency.

1. Uniformity

Several parameters are used as uniformity indicators for the water application into a field. Those most commonly used (Heermann et al., 1990) are given below.

a) Distribution Uniformity (*DU*)

The *DU* indicates the uniformity of application throughout the field and is computed by:

$$DU = 100 * \frac{Z_{iq}}{Z_{av}} \tag{4}$$

Where

Z_{iq} is the average of the lowest one-quarter of the measured values; and,

Z_{av} is the average infiltrated depth in the entire field.

Some authors prefer to replace the low quarter averages in the numerator by the minimum observed depth. This indicator then becomes the absolute distribution uniformity (DU_{abs}) (Pereira 1999).

b) Coefficient of Uniformity (*CU*)

Another parameter that is widely used to evaluate sprinkler irrigation uniformity is the coefficient of uniformity, developed by Christiansen (1942):

$$CU = 100\left(1 - \frac{\sum|Z - m|}{\sum Z}\right) \tag{5}$$

Where

CU is the coefficient of uniformity(%), developed by Christiansen;

*Z*are the individual depths(mm) of catch observations from uniformity test;

|*Z-m*| is the absolute deviation (mm)of the individual observations from the mean; and,

m is the mean depth(mm) of the observations.

Keller and Bliesner (2000) also estimate the system coefficient of uniformity (CU_s) and the system distribution uniformity as:

$$CU_s = \frac{CU}{2}\left[1 + \sqrt{\frac{P_n}{P_a}}\right] \tag{6}$$

and,

$$DU_s = \frac{DU}{4}\left[1 + 3\sqrt{\frac{P_n}{P_a}}\right] \tag{7}$$

Where:P_n is the minimum sprinkler pressure (kPa); and, P_a is the average sprinkler pressure (kPa). Equations 6 and 7 are based on an assumption of normally-distributed data.

2. Efficiency

The concept of efficiency is not well established despite its worldwide utilization. The classical definition of irrigation efficiency proposed by Israelsen (1932) is the ratio between the irrigation water consumed by the crops of an irrigated farm during crop growth and the water diverted from the source (river, canal, or other) during the same time. Jensen (1996) proposed that the term efficiency be restricted to output/input ratios of the same nature, like the ratio diverted/delivered water volumes or applied/infiltrated water depths.

Several factors affect the water application efficiency of sprinkler irrigation systems (Keller and Bliesner 2000):

Variation of individual sprinkler discharge throughout the lateral lines: This variation can be held to a minimum by proper pipe network (to preserve the appropriate nominal pressure) or by employing pressure or flow control devices at each sprinkler or sprinkler nozzle;

Variation in water distribution within the sprinkler spacing area: This variation is caused primarily by wind. It can be partly overcome for set sprinkler systems by close spacing of the sprinklers. In addition to the variation caused by wind, there is variability in the distribution pattern of individual sprinklers. The extent of this variability depends on sprinkler design, operating pressure, and sprinkler rotation.

Losses of water by direct evaporation from the spray: Losses increase as temperature and wind velocities increase, and as drop size and application rate decrease.

Evaporation from the soil surface, before the water is used by the plants: This loss will grow proportionately lower as greater depths of water are applied.

a) Application Efficiency (e_a)

The application efficiency, e_a (%), is defined as:

$$e_a = 100\left(\frac{Z_r}{D}\right) \tag{8}$$

Where:

Z_r is the average depth of water added to the root zone storage (mm); and,
D is the average depth of water applied to the field (mm).

Z_r must be limited to $Z_r \leq SWD$ everywhere in the field, SWD being the soil water deficit (mm) in the root zone at time of irrigation. When this condition is respected, e_a reflects the impact of over-irrigation. This indicator takes into consideration the water runoff and deep percolation (Pereira 1999).

b) Application Efficiency of the Low Quarter ($AELQ$)

The application efficiency of low quarter, $AELQ$ (%), defined by Merriam and Keller (1978) as:

$$AELQ = 100\frac{Z_{r,lq}}{D} \tag{9}$$

Where:

$Z_{r,lq}$ is the average low quarter of water added to root zone storage (mm); and,
D is the average depth of water applied (mm).

As for e_a, the condition $Z_{r,lq} \leq SWD$ is also applied. The fact that Z_r in Eq. (8) is replaced by $Z_{r,lq}$ allows to take into consideration the non-uniformity of water application when under-irrigation is practiced.

c) Potential Efficiency of the Low Quarter (*PELQ*)

The potential efficiency of the low quarter (*PELQ*), in %, which can be used for design and corresponds to the system performance under good management, when the desired depth and timing are applied (Merriam and Keller 1978), can be given as:

$$PELQ = 100\frac{Z_{iq,MAD}}{D_{MAD}} \tag{10}$$

Where:

$Z_{lq,MAD}$ is the average low quarter depth infiltrated (mm) when equal to *MAD*;

$D_{MAD}$is the average depth of water applied when *SWD* = *MAD*; and,

MAD is the management allowed deficit (mm), selected according the crop and the environmental conditions (Martin et al., 1990).

d) Discharge Efficiency (E_d)

The discharge efficiency shows the relation between the water collected by the catch cans and the water discharged by sprinkler. The difference between them is due to evaporation and wind drift losses during the irrigation event:

$$E_a = 100 * \frac{Z_{observed}}{Z_{disch\,\mathrm{arg}\,ed}} \tag{11}$$

Where:

E_d is the discharge efficiency (%);

$Z_{observed}$ is the average water depth(mm) observed at the ground surface; and,

$Z_{discharged}$ is the average water depth discharged (mm).

e) Water Distribution Efficiency (*DE*)

Water distribution efficiency, *DE*, is presented to give more useful meaning to the concept of *CU*. It is expressed as a formula and is based on normal distribution:

$$DE_{pa} = \frac{Minimum\quad net\quad depth\quad received\, by\quad wettest\quad pa\%\quad of\ area}{Average\quad net\quad depth\quad received\quad over\quad entire\quad area} \tag{12}$$

For example, if a sprinkler system has a *CU* of 86%, and a DE_{80} = 85%. This implies that for each unit (mm) of the average application of water received by the crop or soil, 80%of the area would receive 85% of the average application or more, and 20% of the area would receive less than 85%. To apply a net application depth of one unit of water to at least 80% of the area with a system having a CU of 86%, the average net application depth must be:

$$1/0.85 = 1.18 \text{ units of water.}$$

Allen (Allen R.G, 1987) developed an equation for computing the DE_{pa}:

$$DE_{pa} = 100 + (606 - 24.9\, pa + 0.349\, pa^2 - 0.00186\, pa^3)(1 - CU/100) \tag{13}$$

Where:

DE_{pa} is the distribution efficiency for the desired percentage adequacy;
pa is percentage of adequately irrigated area (%); and,
CU is the coefficient of uniformity.

The application efficiency specific to adequacy (% of area receiving the desired net depth) is presented as:

$$Epa = DEpa\, R_e O_e \tag{14}$$

Where:

R_e is the effective portion (0.1-1) of water applied, after estimating the losses by evaporation and wind drift; and,

O_e is the effective portion (0.9-1) of water discharged after estimating the losses by leakage (Keller and Bliesner 2000).

The distribution efficiency can be computed also by taking the average net seasonal depth of irrigation water applied and available for crop use. It can be computed as follows:

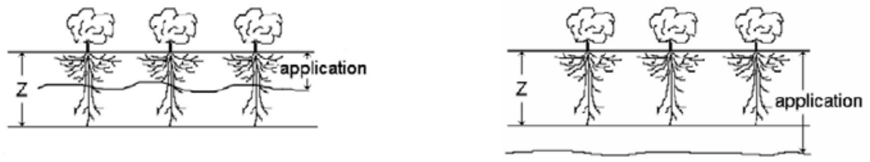
$$DE'pa = 100+(432- 21.3pa + 0.323pa2 - 0.001785pa3)(1-CU/100) \tag{15}$$

The difference between $DEpa$ and $DE'pa$ values for the same CU and pa values represents the difference between the desired net depth, dn and the average net depth available to satisfy crop water-use requirements, d'_n. The value of d'_n will always be less thand_n when some portions of the field are under-irrigated.

Hart and Reynolds (1965) showed that the difference between $DEpa$ and $DE'pa$ are small for high uniformities and/or adequacies of irrigation, but are quite large for the lower uniformities and adequacies.

3. Irrigation Sprinkler Software

Irrigation efficiency is affected by both uniformity and application depth. Uniformity of water distribution mainly depends on design and on subsequent maintenance, while the depth of application is a function of irrigation management. Consequently, it is not enough to have good uniformity of water application when the depth of water applied is not enough to refill the root zone (Figure 6.a) or enough to cause losses by deep percolation and by runoff as shown in Figure 6.b.



(a) (b)

Figure 6 Good irrigation uniformity with inappropriate (low / high) application volume (Merkley and Allen 2006).

The design objective is to assume an acceptable water application uniformity, operating costs, and hardware and installation costs. Nowadays, even though there are hundreds of sprinklers and nozzles with different colors, shapes and characteristics, new sprinklers from several manufacturers still appear on the market. For that reason, a good designer is one who knows how to “select” the appropriate combination of sprinkler, nozzles, and sprinklers layout to achieve water application criteria. Irrigation simulation models have been developed to avoid laborious field tests by assessing water application uniformity under different working conditions. These models can be used as powerful tools in helping sprinkler system designers with their work.

Several software and mathematical model such as SpacePro, Sprinkmod, and Catch3D were developed to simulate the spray pattern over a field based on the distribution characteristics of an individual sprinkler. Each of these is described below.

A. SpacePro Software

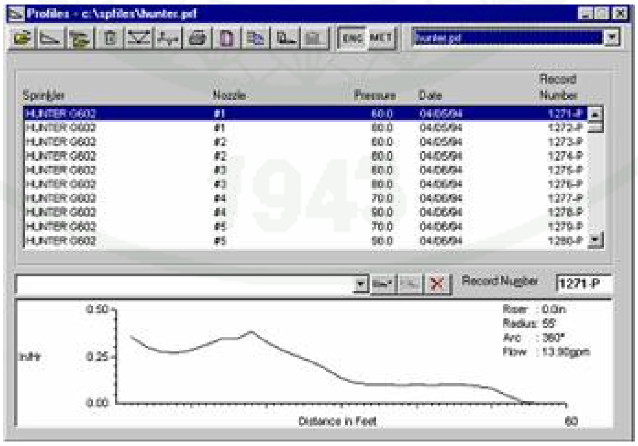
SPACE Pro (Sprinkler Profile and Coverage Evaluation) was developed by the Center for Irrigation Technology (CIT) at Fresno State University.It is a powerful analytical tool giving irrigation designers the ability to evaluate and compare sprinkler designs. SPACE Pro allows designers to place sprinkler heads in almost any configuration and combination; calculate the uniformity and then display the coverage using actual sprinkler test data. Designers can make economic comparisons of different sprinkler layouts to assess the feasibility of upgrading an existing system or choosing a new system.

1. Software Features

SPACE Pro combines all of the features of CIT's popular software programs (SPACE for Windows, Hyper-SPACE, and SPACE Irrigation Survey into a single integrated package. By combining all of these features, SPACE Pro can be used for large turf, commercial, residential and agricultural applications.

a) Sprinkler Data

SPACE Pro provides many different features to obtain and manage sprinkler data. CIT tested sprinkler data and data provided by manufacturers from their testing are available on the CIT web site. Sprinkler data is updated periodically. SPACE Pro can automatically download the sprinkler data and store it on a local computer. There are several features that allow you to create and customize your own files from CIT data, data provided by manufacturers, or from your own testing (Figure 7).



Sprinkler	Nozzle	Pressure	Date	Record Number
HUNTER G602	#1	60.0	04/05/94	1271-P
HUNTER G602	#1	60.0	04/05/94	1272-P
HUNTER G602	#2	60.0	04/05/94	1273-P
HUNTER G602	#2	80.0	04/05/94	1274-P
HUNTER G602	#3	60.0	04/06/94	1275-P
HUNTER G602	#3	80.0	04/06/94	1276-P
HUNTER G602	#4	70.0	04/06/94	1277-P
HUNTER G602	#4	90.0	04/06/94	1278-P
HUNTER G602	#5	70.0	04/06/94	1279-P
HUNTER G602	#5	90.0	04/06/94	1280-P

Record Number 1271-P

Riser : 0.0in
Radius: 55'
Arc : 360°
Flow : 13.90gpm

Figure 7 SPACE Pro water application profile dialog

b) Wide Range of Layout Options

The layout option lets you place any combination of popup and rotors in any configuration. Analyze entire plans or just small sections of larger areas.Layouts can be saved as templates and modified for different uses. Thepopupwill show what sprinkler is currently placed in any head position. And, like the "densograms" for fixed spacing, the application rate is displayed as you move the pointer over the covered area.

c) Editing tools

Editing tools let you block out areas of non-coverage such as sidewalks or driveways. Other tools let you modify and orient variable-arc sprinklers, add entire rows of sprinklers, easily change single heads or entire classes of heads, and adjust run-times for different stations.The Scheduling Coefficient (SC) can be calculated for any size window area you choose and both the driest and wettest areas are displayed.Printouts of the layout can be generated and the printouts identify each head position by sprinkler manufacturer, model, arc, and pressure.

d) Multiple Overlap Options

SPACE Pro can perform rectangular, triangular, equilateral, offset, single- and double-row overlaps.Options are available to control the size and resolution of the overlap grid and to control the size of the window used for calculating the Scheduling Coefficient. Any overlap can be added to a list and used to compare various combinations of sprinkler models, pressures, and layouts. You can also copy the overlap values to the clipboard for export directly into a Microsoft Excel spreadsheet or to export into other programs.

SPACE Pro can display both the driest and wettest areas in the overlap pattern and will display the application rate for that area by simply pointing to any area on the overlap (Figure 8). There is also an option to display the numerical values on screen.

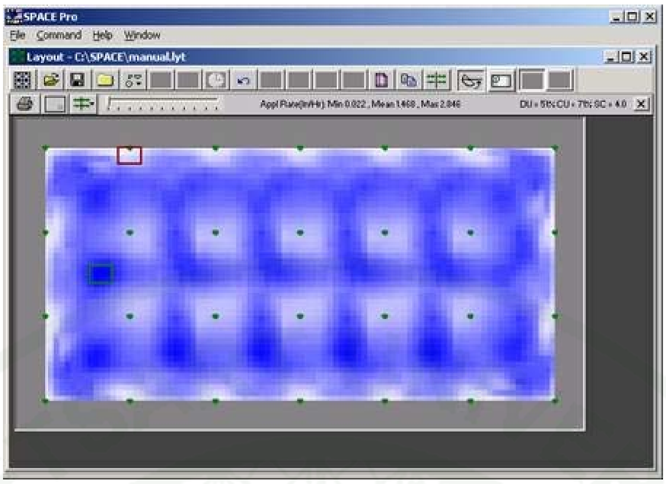


Figure 8 SPACE Pro water application overlap pattern map

e) Economic Analysis Options

SPACE Pro makes it easy to determine the feasibility of upgrading an existing irrigation system or choosing an entirely new system. Any number of overlap spacing, layouts, or pressure and nozzle combinations can be compared to make it easy to determine the economic benefit of upgrading an irrigation system.

Economic analysis is based on the improvement in the Scheduling Coefficient (SC) of the optional system over the current system. The annual cost is the total cost to run the current system per year. The replacement cost is the cost to make the changes needed to replace the current system with the optional system. The interest rate is assumed to be based on a simple interest.

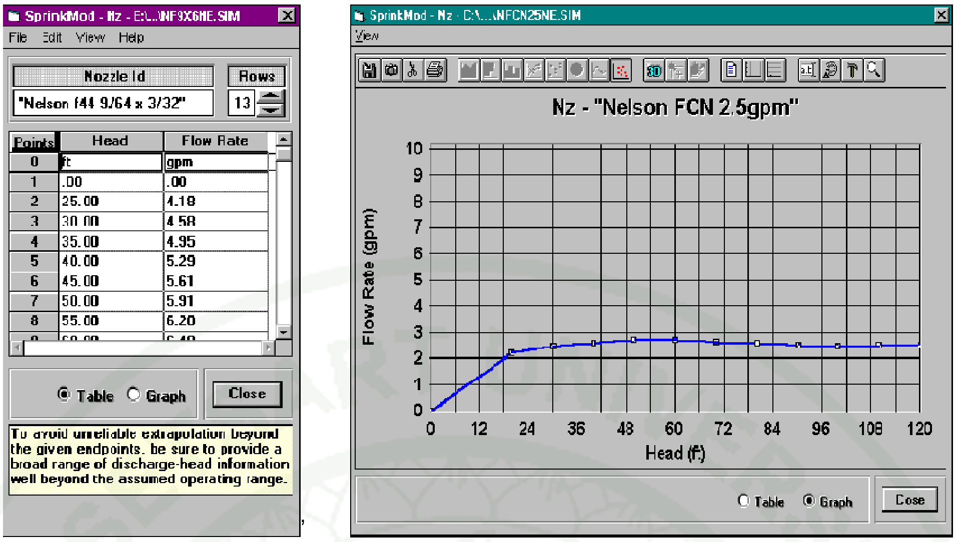
B. Sprinkler Simulation Model (SPRINKMOD)

Sprinkmod was developed by Brazilian Agricultural Research Corporation (EMBRAPA-Brazil) and Utah State University. The computer model was developed to simulate pressure and flow rate distribution along pipes and laterals of pressurized irrigation systems in operation. The software runs in a Windows environment and is capable of simulating irrigation systems having multiple pump stations combined in series and/or in parallel, booster pump stations, parallel pipes and looping pipes. Hand-move, wheel line and center pivot laterals with pressure regulators, one or two drop pipes per outlet and booster pump can be simulated. Leakage can be included in the main pipe network or along the laterals. Lateral inlet pressure can be set to an upper limit to simulate valve closure. Practically any type of nozzle and pump can be simulated since cubic spline functions are used to interpolate values from head-flow rate data sets.

To accomplish these capabilities, algorithms were developed and adapted to convert laterals into a set of head-flow rate data so that a simplified algorithm could be adapted to solve the entire pipe network. A user-friendly interface was designed to allow data for pumps, nozzle and pressure regulators to be interactively entered, edited and analyzed prior to the simulation run. The layout of the irrigation system can be drawn on screen using the mouse. Data can be independently entered and edited for each irrigation system component already drawn in the screen, at any time and in any order. Data for the entire irrigation system are verified at many levels before the simulation is run, to make the model less susceptible to crash. The model proved to be a practical tool for upgrading and designing pressurized irrigation systems but it was never fully developed and has not been in use.

1. Software Features

Important features from pressurized irrigation systems models and from water distribution system models were put together into a new model called SPRINKMOD which stands for “Sprinkler Simulation Model” as show in Figs. 9. To 11. The software package was written in Visual Basic for Windows, version 3.0. It runs in both Windows 3.11 and Windows 95 environments.



Nozzle Id: "Nelson f44 9/64 x 3/32"

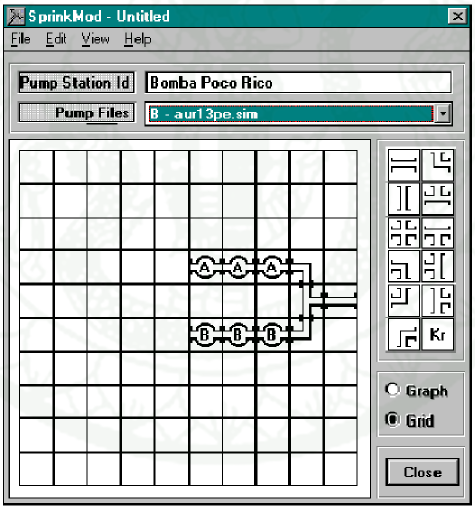
Rows: 13

Points	Head	Flow Rate
0	ft	gpm
1	.00	.00
2	25.00	4.18
3	30.00	4.58
4	35.00	4.95
5	40.00	5.29
6	45.00	5.61
7	50.00	5.91
8	55.00	6.20

● Table ○ Graph

To avoid unreliable extrapolation beyond the given endpoints, be sure to provide a broad range of discharge-head information well beyond the assumed operating range.

Figure 9 Sprinkler data dialog box in SPINKMOD



Pump Station Id: Bomba Poco Rico

Pump Files: B - aur13pe.sim

Figure 10 SPRINKMOD Pump station layout

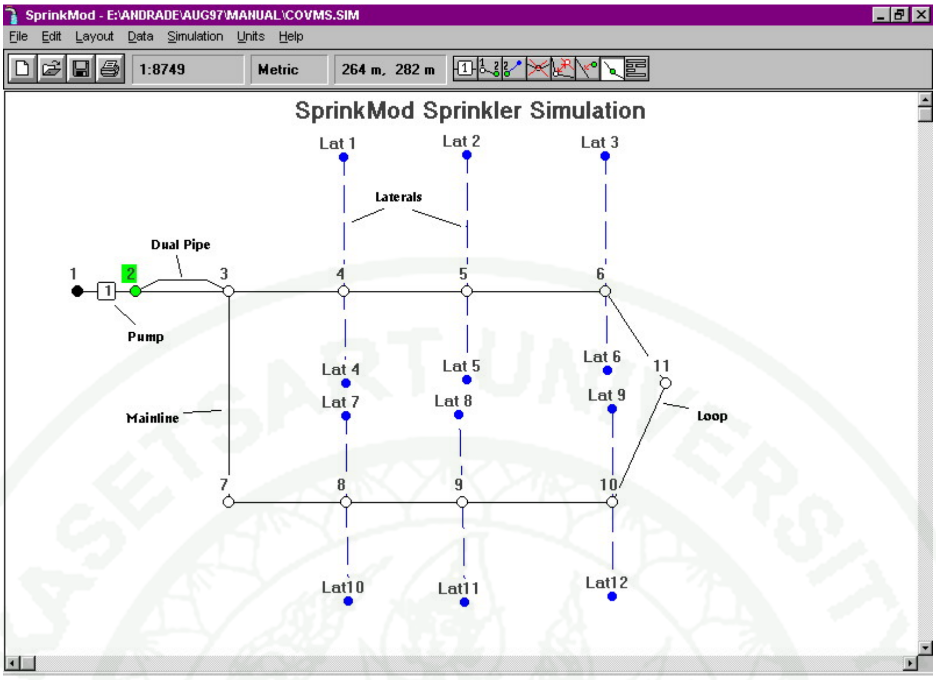


Figure 11 Sprinkler layout dialog

The major features of SPRINKMOD are as follows:

a) Both Metric and English systems of units can be used.

a) Both Metric and English systems of units can be used.

b) Laterals may have one or two tubes per outlet, booster pump, and pressure regulators upstream of nozzles.

c) Laterals with inlet pressure control devices can be simulated.

d) Ground slope and water temperature can be varied for each lateral pipe segment and for each network pipeline.

e) Pumps in a pump station can be combined in series and/or in parallel within the model.

f) Booster pump stations can be placed in any part of the pipe network.

g) Pipe networks with multiple sources of water or multiple pump stations can be simulated.

h) Networks with pipes in parallel and with looping pipes can be simulated.

i) A user-friendly interface provides easy data entry and editing for pumps, nozzles and pressure regulators.

j) The layout of any pressurized irrigation system can be drawn on the screen and can be fully edited by using the mouse.

k) Data for the irrigation system components can be interactively entered and edited.

C. CATCH3D

Catch3D was developed at Utah State University. Catch3D is a mathematical model for statistically analyzing measured performance data for agricultural sprinklers, with emphasis on application uniformity and efficiency calculations. It is used for evaluating the performance of specific configurations and operating conditions for sprinklers, including the simulated overlapping of sprinkler application patterns. For example, the model can help decide which sprinkler spacing will give the best application uniformity.

The model is interactive and has comprehensive internal data checking and cross-checking features, but it is, nevertheless, intended for use by irrigation specialists who are knowledgeable about the technical features and issues of pressurized agricultural irrigation systems. The most useful and applicable results from the software can best be obtained from such specialists. For this reason, this users guide includes a technical reference with a number of appendices that explain many of the technical details of the software implementation and theoretical basis.

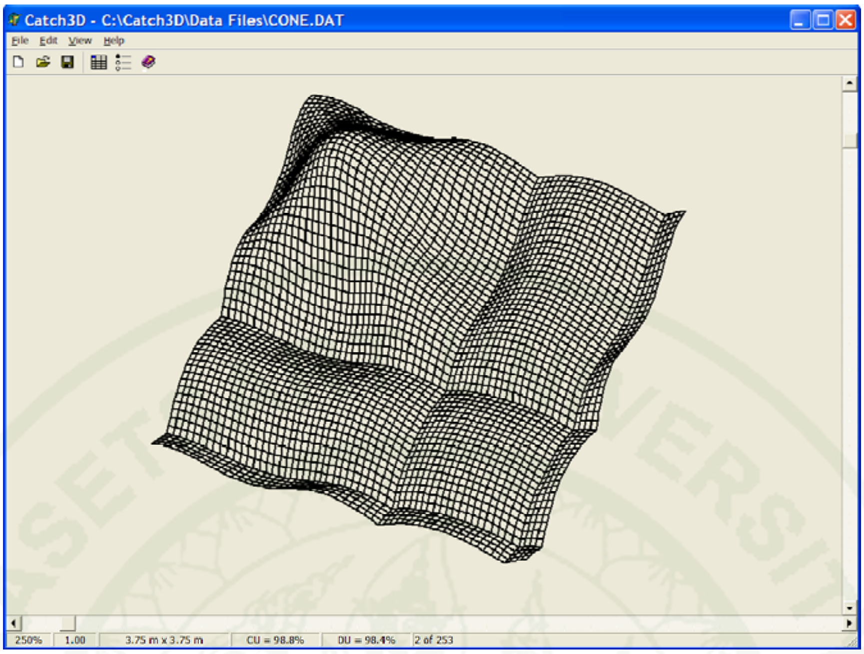


Figure 12 Wireframe view of sample overlapped catch data in the main window

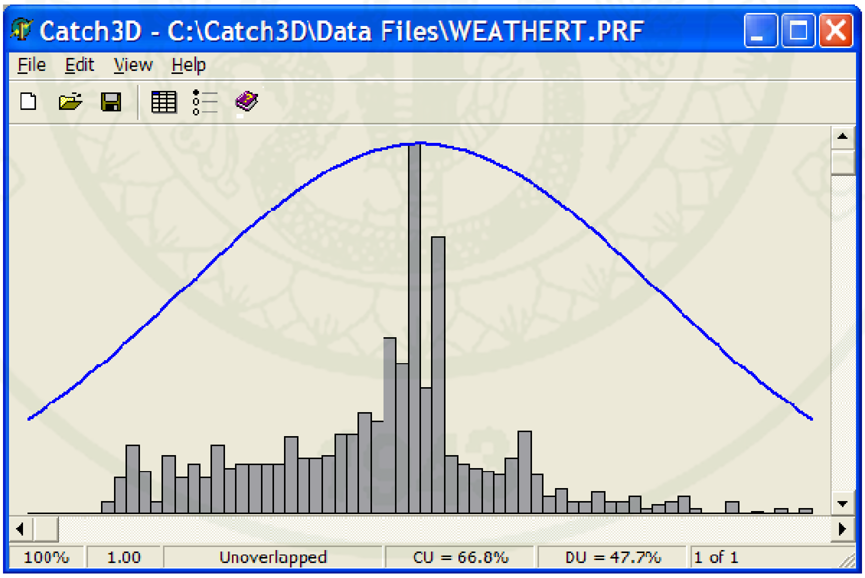


Figure 13 A histogram of sample unoverlapped catch data in the main window

MATERIALS AND METHODS

Materials

The development of sprinkler layout software required the following materials. The software was developed by using Visual basic .NET programming language The developed modeling was tested using personal computers CPU 3.0 GHz with 1 GB of RAM. Finally, several official apparatus such as a printer, paper, etc were also required to complete this work.

Methods

1. Overview of Sprinkler Design Software

A. Irrigation Sprinkler System Design

Sprinkler irrigation design can be separated to three main parts: (1) specification of cropping patterns; (2) achieving a water application uniformity target; and, (3) designing the pipe system. The cropping patterns are determined by both the farm owner and the local climatic conditions, and crop types, planting dates, and weather are the main factors in determining cropwater demand. Although the weekly water demand in the planted area can be approximated, and is usually expressed in units of millimeters of depth, the required gross quantity of water in a given area may also depend on the soil type. Moreover, irrigation scheduling depends on the soil water-holding capacity and on the infiltration rate in the planted area. Some soils have a relatively high water-holding capacity and low infiltration rate (e.g. some clay soils), while others (e.g. sandy soils) have low water-holding capacity and high infiltration rate. After estimating the quantity of water delivery, the next step is to determine the locations of sprinklers in the planted area.

Water application uniformity is influenced by sprinkler characteristics, discharge, pressure, sprinkler spacing, sprinkler spacing pattern (usually triangular or rectangular), wind and other factors. After the locations of each sprinkler in the planted area are determined for a given design alternative, the next step is to design the pipe layout according to the field topography, required nominal sprinkler flow rate and corresponding pressure. The sprinkler layout design software which was developed in this study consists of three main parts as follows:

1. Sprinkler system layout parameters;
2. Algorithms for sprinkler layout design; and,
3. System integration and development.

The details of the methodology and algorithms for developing the software are described below.

B. Software Development

In general, software design and development consists of three activities, or components: (1) pre-processing; (2) processing; and, (3) post-processing. These three components can work both dependently and independently. Likewise, the above concept was applied in this software development procedure. From the initial idea, the design and development of software should be a semi-automatic system which requires interaction between the program and its user.

The sprinkler design software described herein includes the following components:

1. Basic design data;
2. Sprinkler database;
3. Pipe layout algorithm;
4. Pipe hydraulic model; and,
5. Water application uniformity.

This software encapsulates these five components to perform the design irrigation sprinkler layouts. The system development diagram of the entire design process is illustrated in Figure 14, in which the five components are highlighted.

C. Methodology for Developing the Sprinkler System Layout Design Software

The software which is a product of this research is called sprinkler system layout design software, a collaboration between Utah State University (USU) and Kasetsart University (KU), so it is referred to in brief as USUKU. Similar to the software development document, the development of USUKU was divided into three parts:

- Sprinkler system layout design data;
- Algorithms for sprinkler layout design; and,
- System integration and development.

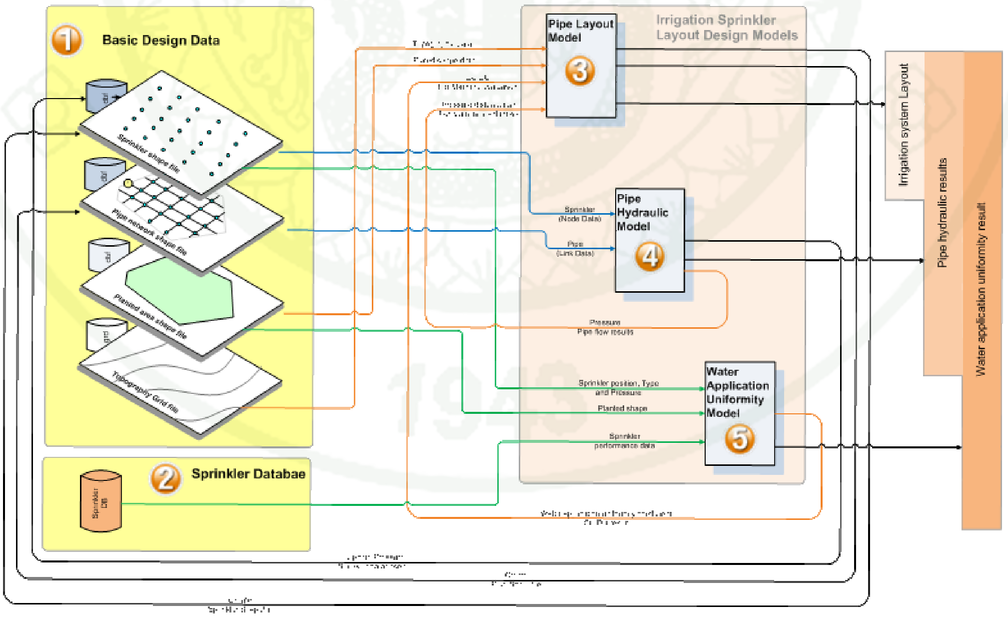


Figure 14 Sprinkler layout software design diagram

2. Sprinkler System Layout Design Data

Sprinkler system layout design parameters consist of geometric data, sprinkler performance data, and pipe data. Details of each parameter category are described in the following subsections.

A. Geometric Data

Geometric data are those that are usually obtained from a field survey. In this study, the geometric data include topographic data, planted area, and land use data. These data can be visualized in different mapping formats; for example, the topographic data can be presented in a contour map, or the planted area can be bounded inside a polygon map, and so on. The major geometric data required for USUKU are the topographic data and the shape of the planted area.

1. Topographic Data

Topographic data represent the surface shape and features of the area. The topographic data of the sprinkler area can be obtained from a field survey and they are recorded in an (x, y, z) Cartesian coordinate system. The next step is to convert the coordinates to a grid system, as shown in Figure 15, by using gridding techniques such as Inverse Distance or Moving Average.

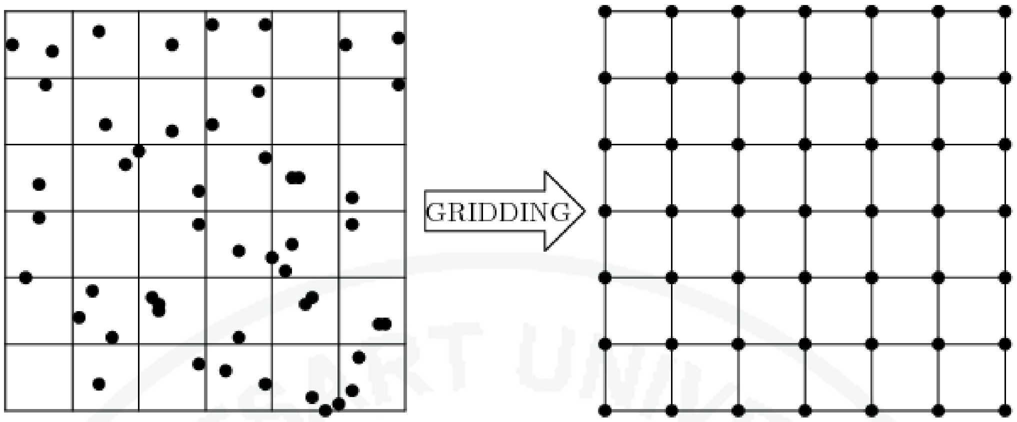
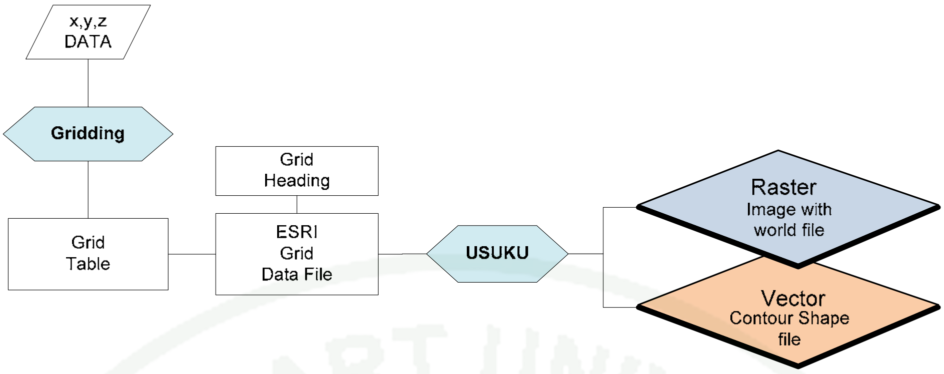


Figure 15 Schematic defining the conversion of topographic data to a grid

At this stage, the grid system can be accessed using a spreadsheet program, but it is not yet ready to input to the USUKU program. It requires additional work to convert the grid system to the specific format (i.e. ESRI grid, or *.asc file). In general, the grid system developed by ESRI (Environment System Research Institute, Redlands, California) is a raster file that is expressed in either binary or ASCII format. For details, the interested reader is referred to http://en.wikipedia.org/wiki/ESRI_grid.nge.

The grid system is defined as a two-dimensional array which stores the elevation data in both rows and columns. The topographic grid is a grid system that stores the elevation in each grid cell and it used to referenced to an (x, y) coordinate system. USUKU prepares the grid data to generate two data types: raster and vector formats, which represent the topographic image and contour lines, respectively. A flow chart of the topographic data input process in the USUKU program is depicted in Figure16.



Note: Invert distance is gridding technique for USUKU

Figure 16 USUKU topographic data input process

2. Shape of the Planted Area

The planted area, as a polygon shapefile, is one of the inputs to USUKU. For the data file (shapefile), many polygon shapes are imported into the program, but only the first polygon shapefile is used to represent the planted area. The polygon shapefile can be drawn directly on the map by using a tool provided in USUKU. The user has two alternatives to build the planted shapefile: (1) convert from the (x, y) coordinates at a vertex of the planted area; or, (2) use the GIS drawing tool. Of course, the (x, y) coordinates can be obtained from the GPS tool through the field survey. The flowchart in Figure17 shows the steps for building the planted-area polygon in the USUKU program.

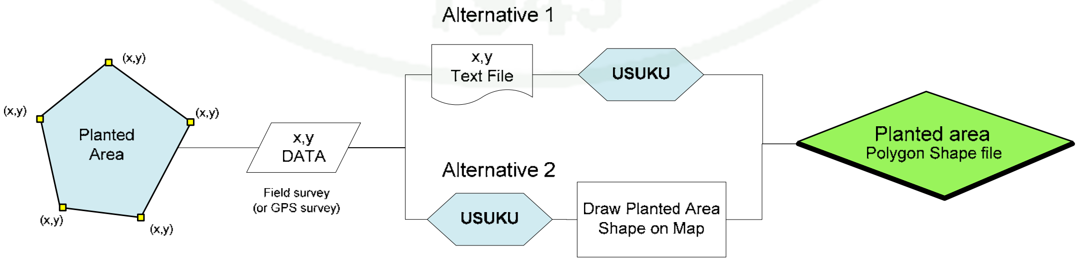


Figure 17 Planted area shape file creation process

Note that the necessary geometric data for USUKU includes the topographic and planted-area data which are expressed in the ESRI shapefile format.

B. Sprinkler Performance Data

The sprinkler performance data can be also retrieved from a catch-can test. The required water application uniformity data for a sprinkler can be obtained from a single sprinkler test by varying the type and pressure that cover the possible pressures that might be found in the sprinklermanufacturer’s manual. Figure18 illustrates the testing concept for this study. As can be seen, the water application rates at different pressures and sprinkler types (Figures19 to 20) are inputted and managed in the database software.

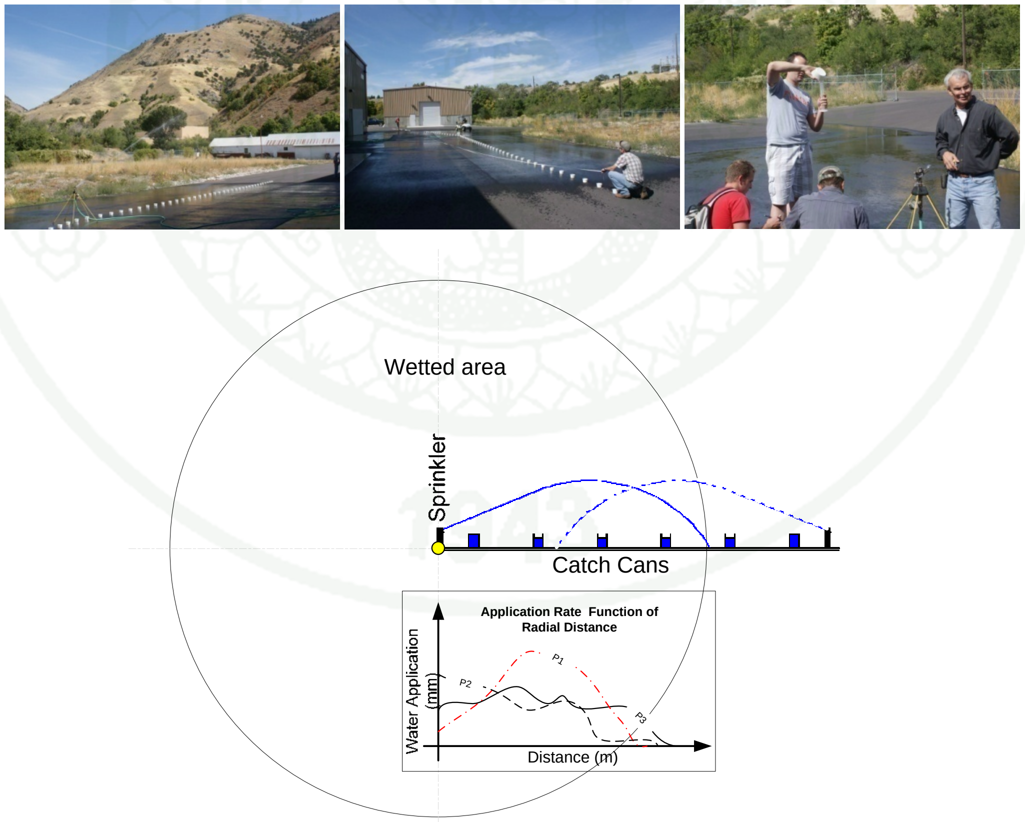


Figure 18 Water application testing concept

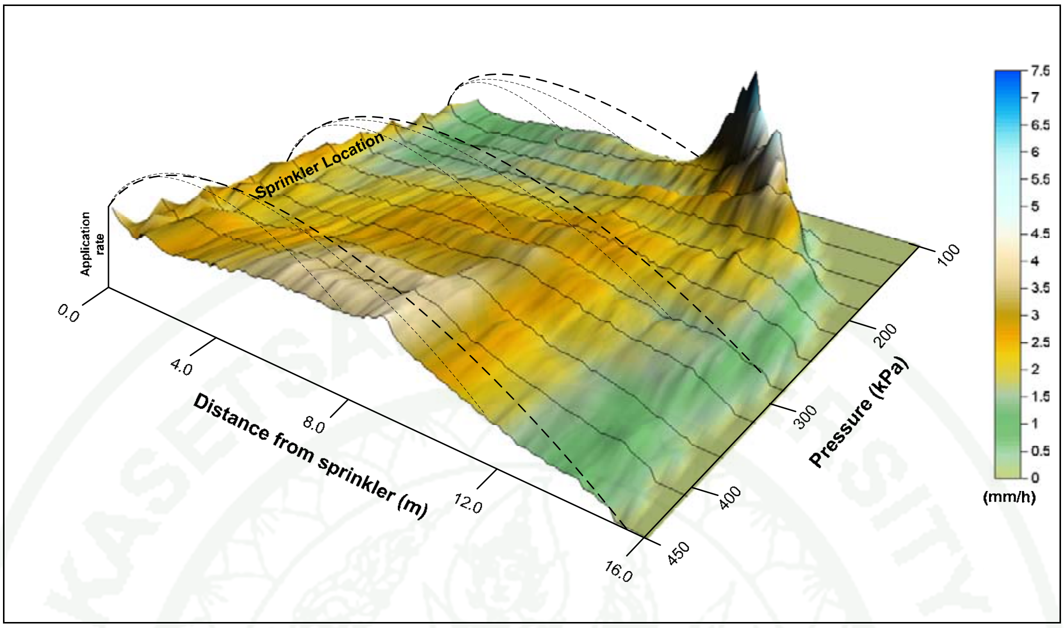


Figure 19 Water application rates for a Nelson R33 sprinkler

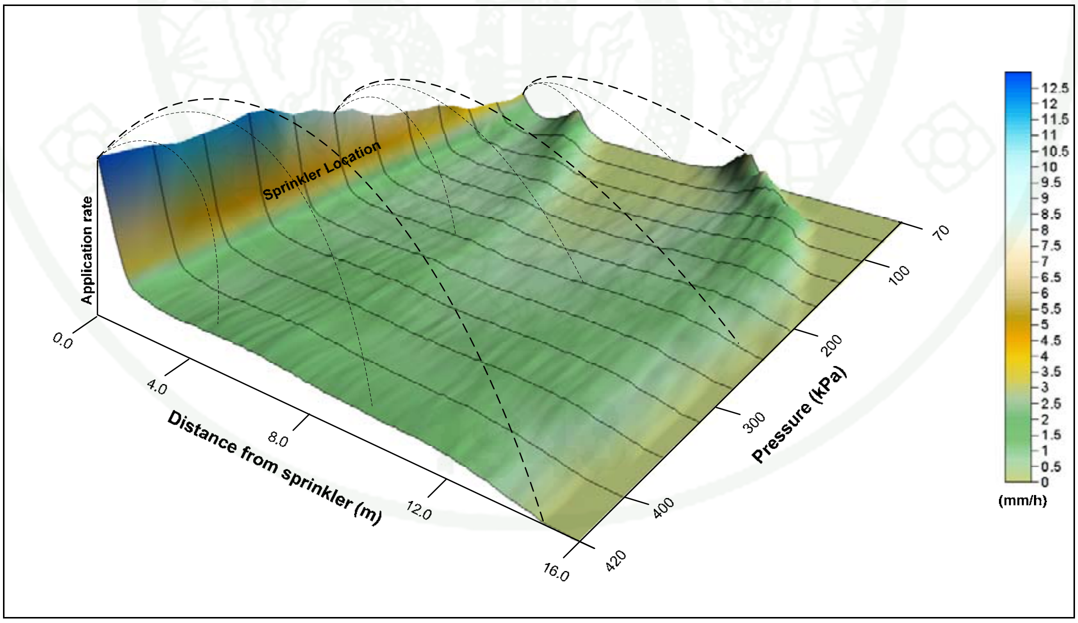


Figure 20 Water application rate for a Rainbird Mini Paw/LG-3 sprinkler

3. Commercial Pipe Data

Discrete pipe sizes were used in this study and for a specific locale one can refer to the pipe size information available by vendors in the market. The important pipe data for hydraulic calculations are the inside diameter and pipe material (so as to know the surface roughness). Moreover, the pipe cost is also an important factor in the pipe-size optimization process. In this study there were a total of 462 commercial pipe data records which were obtained from pipe suppliers. The pipe database is summarized in Table 2.

Table 2 Data sample from the commercial pipe database in USUKU

Material	Class	Roughness (H-W C)	Diameter (mm)	Nominal Size	Wall Thickness (cm)	Weight (lbs/ft)	Mass (kg/m)
Cast Iron	Class A	0.0048	80	3" I/D	0.400	13.246	20.00
Cast Iron	Class A	0.0048	100	4" I/D	0.400	17.142	25.88
Cast Iron	Class A	0.0048	150	6" I/D	0.450	28.270	42.68
Cast Iron	Class A	0.0048	200	8" I/D	0.525	43.593	65.81
Cast Iron	Class A	0.0048	250	10" I/D	0.550	56.516	85.31
Cast Iron	Class A	0.0048	300	12" I/D	0.600	73.635	111.16
Cast Iron	Class A	0.0048	400	14" I/D	0.650	92.749	140.01
Cast Iron	Class A	0.0048	400	16" I/D	0.700	113.861	171.88
Cast Iron	Class A	0.0048	450	18" I/D	0.750	136.969	206.76
Cast Iron	Class A	0.0048	500	20" I/D	0.800	162.074	244.66
Cast Iron	Class A	0.0048	600	24" I/D	0.900	218.274	329.50
Cast Iron	Class A	0.0048	800	30" I/D	0.870	261.587	394.88
Cast Iron	Class A	0.0048	800	36" I/D	0.980	352.982	532.85
Cast Iron	Class A	0.0048	800	42" I/D	1.100	461.774	697.08
Cast Iron	Class A	0.0048	900	48" I/D	1.250	599.620	905.16
Cast Iron	Class A	0.0048	1400	54" I/D	1.330	716.757	1081.99
Cast Iron	Class A	0.015748	80	3"	0.390	12.953	19.55
Cast Iron	Class A	0.015748	100	4"	0.420	17.918	27.05
Cast Iron	Class A	0.015748	150	6"	0.440	27.685	41.79
Cast Iron	Class A	0.015748	200	8"	0.460	38.487	58.10
Cast Iron	Class A	0.015748	250	10"	0.500	51.622	77.93
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
Cast Iron	Class B	0.015748	800	42"	1.280	538.833	813.40
Cast Iron	Class B	0.015748	900	48"	1.420	682.966	1030.98
Cast Iron	Class B	0.015748	1400	54"	1.550	838.640	1265.98
Cast Iron	Class B	0.015748	1500	60"	1.670	1004.090	1515.73

3. Algorithms for Sprinkler System Layout Design

A. Geometry Classes

While USUKU already provides the necessary geo-functionality for sprinkler layout design, the full geo-functionality for shape display was provided from the MapwinGIS component. The geo-function and geo-properties for USUKU were designed for operating the following four basic shapes:

1. Point shape;
2. Line shape;
3. Poly line shape (path); and,
4. Polygon shape.

The MapwinGIS component (mapwindow.ocx) provides many geo-functions, but it doesn't have a precise geo-function for the sprinkler layout design process. The geo-function for USUKU was developed to support these three parts of the automated design process:

1. System pipe layout;
2. Pipe hydraulic model; and,
3. Water application uniformity.

In conclusion, the Visual Basic geometry class in USUKU was created using 15 geo-properties as well as 84 geo-functions which are not found in MapwinGIS. Some of the USUKU functions and properties are similar to those of MapwinGIS, but they have different function arguments which are not provided by MapwinGIS. The list of USUKU geo-functions and properties are shown in Table 3.

Table 3 Summary of geo-functions in USUKU

ID	NAME	Argument
API-001	CreatePolygonRgn	*CreatePolygonRgn Lib "gdi32" (lpPoint As Any, ByValnCount As Long, ByValnPolyFillMode As Long) As Long*
API-002	RtlMoveMemory	*RtlMoveMemory Lib "kernel32" (dst As Any, src As Any, ByValnBytes&)*
EVT-001	Sorting	*Scoring()*
GA-001	Breed_Them	*Breed_Them()*
GA-002	Init_Generation	*Init_Generation*
GA-003	Eval_Value	*Eval_Value(ID, num As Bloobs) As Single*
GA-004	Eval_Fitness	*Eval_Fitness(num As Bloobs) As Single*
GA-005	Pop_Sort	*Pop_Sort(popi() As Bloobs) As Bloobs()*
GA-006	Show_BestGen	*Show_BestGen()*
GA-007	Mating_Season	*Mating_Season()*
GA-008	CrossOver	*CrossOver(a As Single, b As Single) As Single*
GA-009	LongToBit	*LongToBit(L As Long) As String*
GA-010	BitToLong	*BitToLong(bitexpr As String) As Long*
GA-011	ChemicalX	*ChemicalX(inbloob As Bloobs) As Bloobs*
GA-012	BitToggle	*BitToggle(ByVal Value As Long, ByVal bit As Long) As Long*
GA-013	Child_to_Adult	*Child_to_Adult()*
GEO-001	LineGIS	*Function LineGIS(X1, Y1, x2, y2, Lwidth As Long, LColor As Long) As Boolean*
GEO-002	PointGIS	*PointGIS(X1, Y1, Pwidth As Long, PColor As Long)*
GEO-003	Centroid	*Centroid(BoundaryPath As PathType, ByRefCentroidPoint As POINTAPI)*
GEO-004	PathArea	*PathArea(mPath As PathType)*
GEO-005	Length	*Length(mLine As LineType)*
GEO-006	PathLength	*PathLength(Pth As PathType)*
GEO-007	PointInPath	*PointInPath(Pth As PathType, Dist, ID)*
GEO-008	PointInLine	*PointInLine(L As LineType, subDist) As POINTAPI*

Table 3 (Continued)

ID	NAME	Argument
GEO-009	diffX	*diffX(mLine As LineType)*
GEO-010	diffY	*diffY(mLine As LineType)*
GEO-011	AzmAngle	*AzmAngle(mLine As LineType)*
GEO-012	spiltRegion	*spiltRegion(ID, id1, p1 As POINTAPI)*
GEO-013	PolygonArea	*PolygonArea(nPoints, R_Point() As POINTAPI)*
GEO-014	MidLine	*MidLine(mLine As LineType) As POINTAPI*
GEO-015	Line_Line	*Line_Line(a As LineType, b As LineType, desx, desy) As Boolean*
GEO-016	Point_Line	*Point_Line(X, Y, P As LineType) As Boolean*
GEO-017	PointInPolygon	*PointInPolygon(Points() As POINTAPI, X, Y) As Boolean*
GEO-018	Intersect	*Intersect(p1 As POINTAPI, p2 As POINTAPI, p3 As POINTAPI, p4 As POINTAPI) As Boolean*
GEO-019	CCW	*CCW(p0 As POINTAPI, p1 As POINTAPI, p2 As POINTAPI) As Long*
GEO-020	ParallelLine	*ParallelLine(L1 As LineType, L2 As LineType) As Boolean*
GEO-021	PerpendicularLine	*PerpendicularLine(L1 As LineType, L2 As LineType) As Boolean*
GEO-022	Offset	*Offset(Dx, p1 As POINTAPI, p2 As POINTAPI) As POINTAPI*
GEO-023	DLengthPosition	*DLengthPosition(p1 As POINTAPI, p2 As POINTAPI) As POINTAPI*
GEO-024	Line_Circle	*Line_Circle(P As LineType, k As CircleType, desx1, desy1, desx2, desy2) As Integer*
GEO-025	My_Sgn	*My_Sgn(X) As Integer*
GEO-026	PerpendicularPoint	*PerpendicularPoint(L1 As LineType, L2 As Single)*
GEO-027	Perpend2Point	*Perpend2Point(L1 As LineType, mp As POINTAPI)*
GIS-001	OpenTopo	*OpenTopo(Fname As String) As Boolean*

Table 3 (Continued)

ID	NAME	Argument
GIS-002	AddShapefile	*AddShapefile(FileName As String)*
GIS-003	LoadPlantedArea	*LoadPlantedArea(Fname As String)*
GIS-004	DrawPlantedBoundary	*DrawPlantedBoundary()*
GIS-005	GetEle	*GetEle(X1, Y1)*
MLF-004	ArialEvaluate	*ArialEvaluate(A1, A2)*
MLF-005	UnifLatEvaluate	*UnifLatEvaluate(mVal)*
MLF-006	MReEvaluate	*MReEvaluate(mVal)*
MLF-007	SEEvaluate	*SEEvaluate(mVal)*
MLF-008	UpNDownHEvaluate	*UpNDownHEvaluate(mVal)*
MLF-009	MainLineSprinklerPoistion	*MainLineSprinklerPoistion(Optional Fname As String)*
MLF-010	PerpendEvaluation	*PerpendEvaluation(mVal)*
MLF-011	PerpendEvaluation	*PerpendEvaluation()*
RSQ-001	Build_Matrices	*Build_Matrices(N, ZigmX, ZigmX2, ZigmXZ, ZigmY, ZigmY2, ZigmYZ, ZigmXY, zigmZ)*
RSQ-002	Build_Triangular_Matrix	*Build_Triangular_Matrix()*
RSQ-003	Back_Substitution	*Back_Substitution(b0, b1, b2)*
RSQ-004	R2	*R2(b0, b1, b2, spPoint() As POINTAPI)*
RSQ-005	SEE	*SEE(b0, b1, b2, spPoint() As POINTAPI)*
MLF-012	ParallelScan	*ParallelScan()*
MLF-013	VertexAngleScan	*VertexAngleScan()*
GEO-028	PointTodist	*PointTodist(Pth As PathType, pp1 As POINTAPI) As Single*
GEO-029	pointOnBC	*pointOnBC(LL As LineType, bc As PathType, pp1 As POINTAPI, pp2 As POINTAPI) As Boolean*

B. System Pipe Layout Methodology

The basic data for the mainline alignment process (with respect to the planted area) are geometric data (topography and shape of the planted area). In USUKU, the mainline guide is represented by a line shape that can be defined by two points on the boundaries of the planted area, as seen in Figure21. Therefore, the sprinkler laterals are the lines which are perpendicular to the mainline, as shown in Figure21. Basically, the user can define the mainline location by drawing a line which intersects two sides of the planted area. Nevertheless, USUKU includes a topographic algorithm for suggesting a collection of the best guides for mainline location. The flowchart of the pipe system layout algorithm is shown in Figure22.

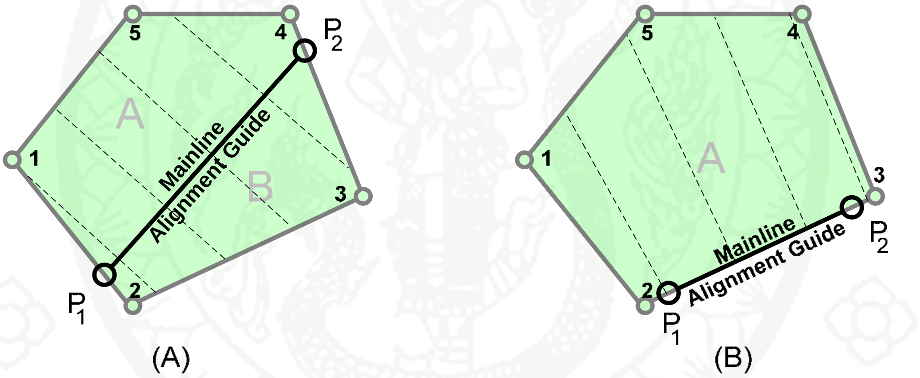


Figure 21 Planted area(s) separated by the mainline alignment guide

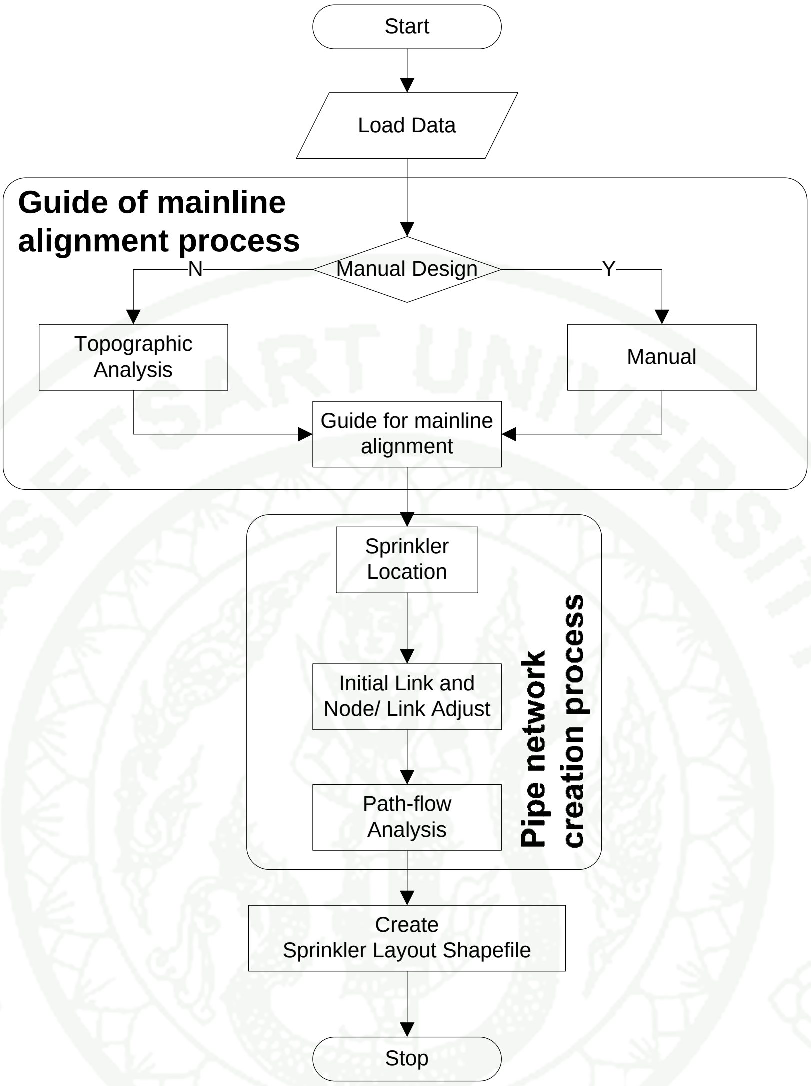


Figure 22 Flowchart for pipe system layout data creation

1. Topographic Analysis

To obtain a uniform application of water along the length of a lateral, pipe diameter, length, and alignment must be selected so as to result in a minimum variation in discharge between individual sprinklers. Normally, the variation in discharge should not exceed 10% unless it is economically justified. Therefore, either pressure (or flow) regulation may need to be provided for each sprinkler, or laterals must be located and pipe sizes selected so that the pressure head variation in the laterals, due to both friction loss and elevations differences, will not exceed 20% of the average design operating pressure for the sprinklers. To meet this pressure variation criterion, it is usually preferable to lay laterals on elevation contours (Keller and Bliesener 2000) or along prominent cross slopes.

a) Topographic Type for Mainline Alignment

A topographic map is a type of map characterized by large-scale detail and quantitative representation of relief, usually using contour lines in modern mapping. Topographic data are the basic data for sprinkler layout design, because they indicate main-line and lateral-lines of a system. For this study, there are five cases of sprinkler layout topographies. However, all topographic cases have a similar shape, as depicted in Figure23, and all details are shown in Figures24 to 28.

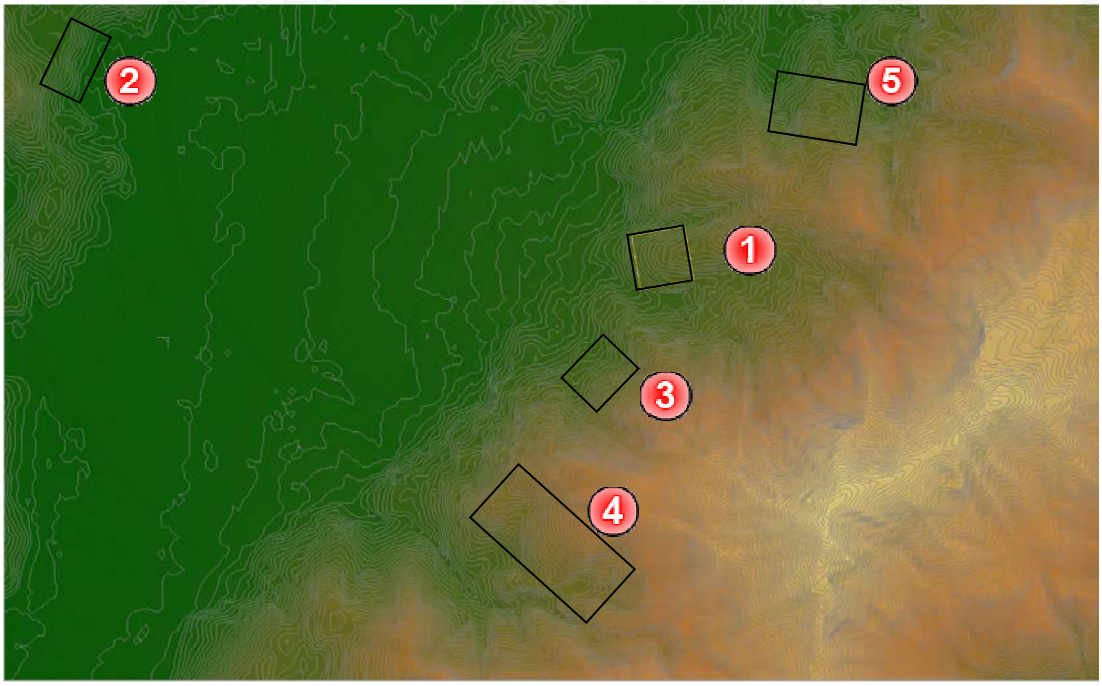


Figure 23 Various planted area locations overlaid on a topographic map

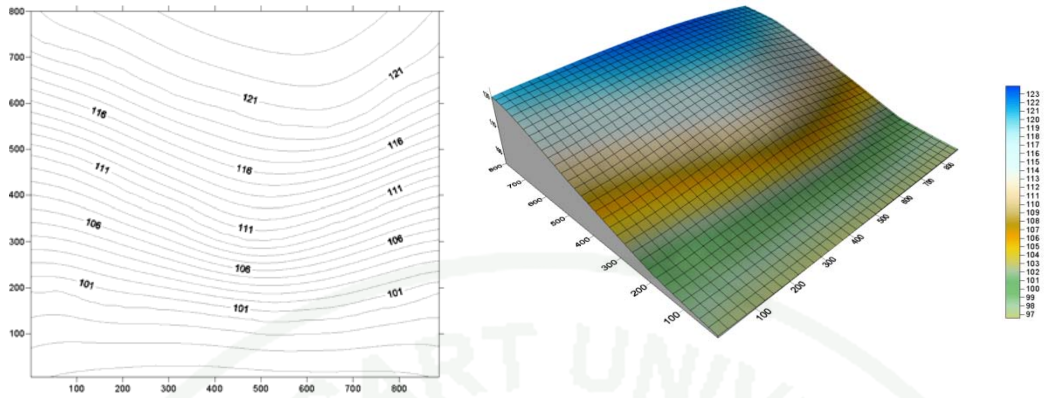


Figure 24 Type I topography

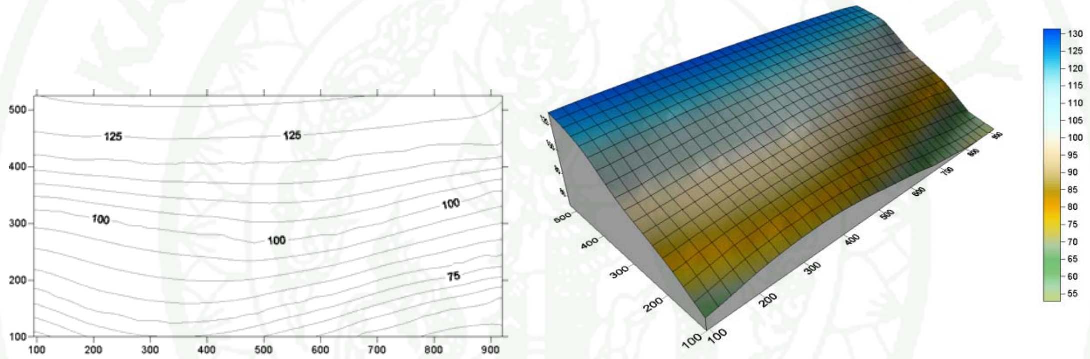


Figure 25 Type II topography

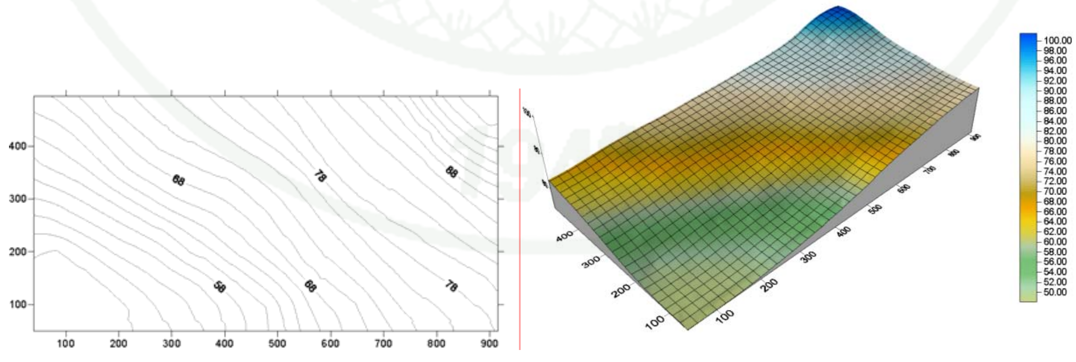


Figure 26 Type III topography

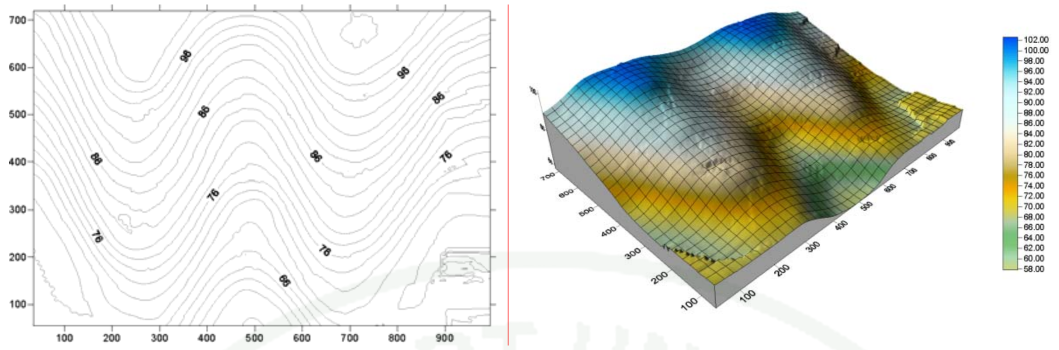


Figure 27 Type IV topography

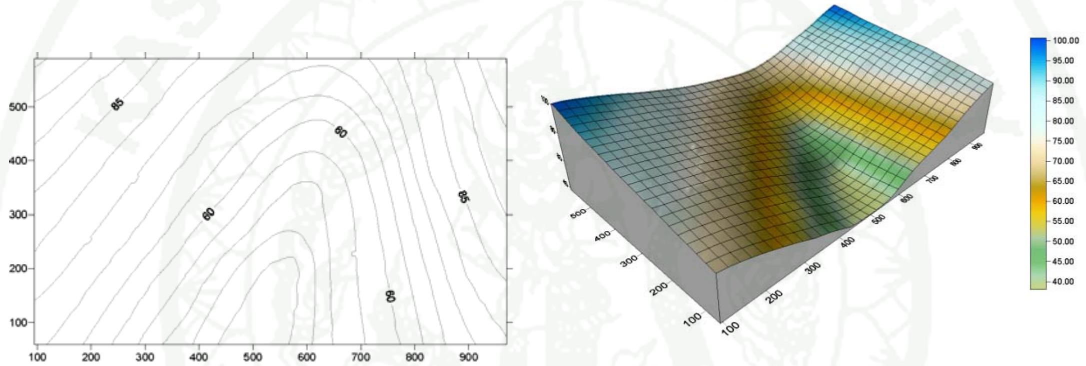


Figure 28 Type V topography

b) Terrain Analysis

Terrain data for USUKU are those which are mentioned above. The important terrain evaluation parameters are: (1) terrain slope; (2) terrain aspect; (3) profile curvature; (4) plan curvature; (5) tangential curvature; and, (6) single flow direction map (Golden Software 2002).

(1) Terrain Slope

Terrain slope is calculated from the slope of any grid of DEM (**D**igital **E**levation **M**odel) on the surface. Terrain slope is reported in degrees from zero (horizontal) to 90 (vertical). For a particular point on the surface, the terrain slope is based on the direction of steepest descent or ascent at a point (Terrain Aspect). This means that across the surface, the gradient direction can change the grid field of the terrain slope, and can produce contour maps that show isolines of constant steepest slope. This operation is similar to the way the first directional derivative defines the slope at any point on a surface, but it is more powerful in that it automatically defines the gradient direction at each point on the map. The slope, S, at a point P is the magnitude of the gradient at that point.

(2) Terrain Aspect

Terrain aspect is calculated from the downhill direction of the steepest slope (i.e. dip direction) at each grid of DEM. It is the direction that is perpendicular to the contour lines on the surface, and is exactly opposite the gradient direction. Terrain Aspect values are reported in azimuth, where 0 degrees points due North, and 90 degrees due East (Moore et al. 1993).

(3) Profile Curvature

Profile Curvature is using for determining the downhill or uphill rate of change in slope in the gradient direction at each grid DEM. The profile curvature product is a contour map that shows isoclines of constant rate of change of steepest slope across the surface. This operation is comparable to the second directional derivative but is more powerful because it automatically determines the downhill direction at each point on surface, and then determines the rate of change of slope along that direction at that point. Negative values are convex upward and indicate the potential ofan accelerated flow of water over the surface. Positive values are concave upward and indicate slower flow over the surface.

(4) Plan Curvature

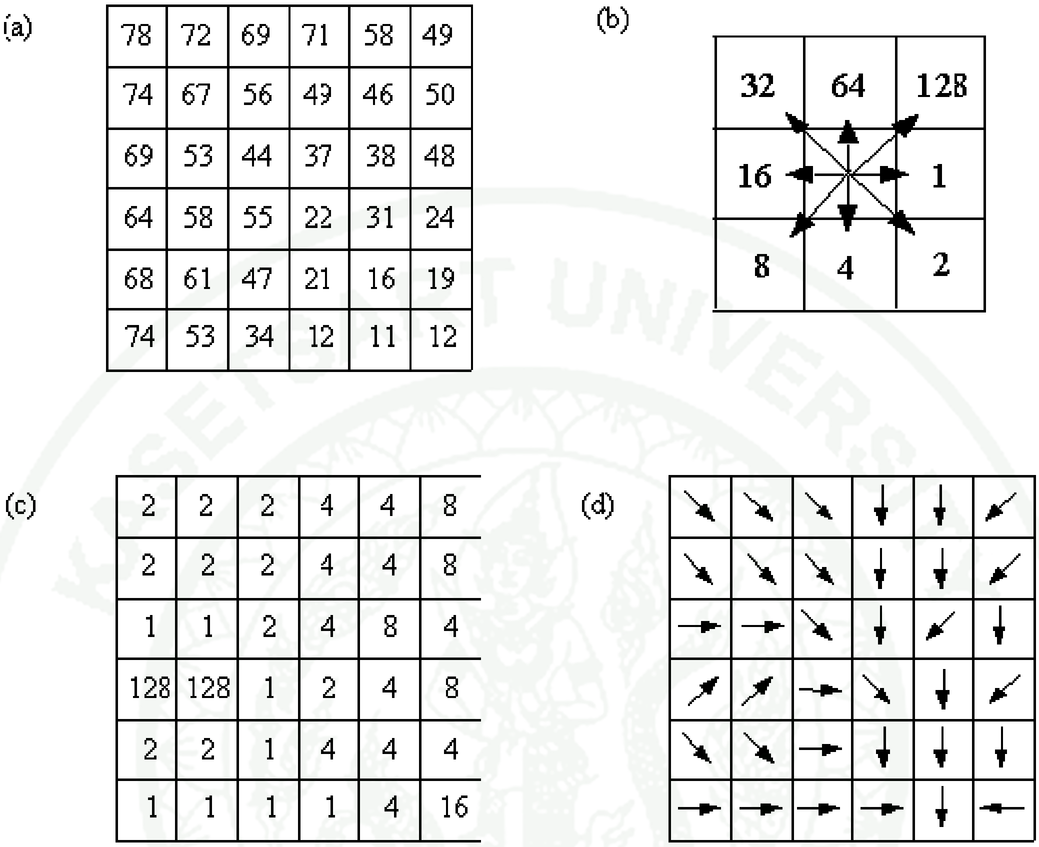
Plan Curvature is a parameter that reflects the rate of change of the terrain aspect angle measured in the horizontal plane, and is a measure of the curvature of contours. Negative values indicate divergent water flow over the surface, and positive values indicate convergent flow.

(5) Tangential Curvature

Tangential curvature is the curvature in thehorizontal plane as shown in Figure 21. It measures curvature in relation to a vertical plane perpendicular to the gradient direction, or tangential to the contour. The negative and positive areas are the same as for plan curvature, but the curvature values are different.

(6) Single Flow Direction Maps

Several models for defining a grid of flow directions based on a DEM are discussed in the literature and good reviews of these methods are provided by Tarboton (1997) and Costa-Cabral and Burges (1994) each of whom introduces their own methods. The simplest and most widely used method (often referred to as the D8 method) to define flow directions in DEMs is described by O'Callaghan and Mark (1984) and Jensen and Domingue (1988). In the D8 model, it is assumed that a water particle in each DEM cell flows towards one and only one of its neighboring cells that cell being the one in the direction of steepest descent. To assign a flow direction value to a cell, the "distance weighted drop" to each of eight neighboring cells is computed by taking the difference in elevation values and dividing by $\sqrt{2}$ for a diagonal cell and by one for a non-diagonal cell. The flow direction for a cell is assumed to be in the direction with the highest distance weighted drop. In situations where multiple adjacent cells have equal drops or where all adjacent cells have no drop (flat areas), special considerations are made (Jenson and Domingue, 1988). The eight possible flow directions are assigned unique numbers based on the following convention (East = 1; Southeast = 2; South = 4; Southwest = 8; West = 16; Northwest = 32; North = 64; Northeast = 128). Figure 29(a) shows an example elevation grid, Figure 29(b) shows the flow direction assignment convention, Figure 29(c) shows the numerical values assigned to cells in the flow direction grid, and Figure 29(d) shows the flow directions symbolically with arrows.



(a)

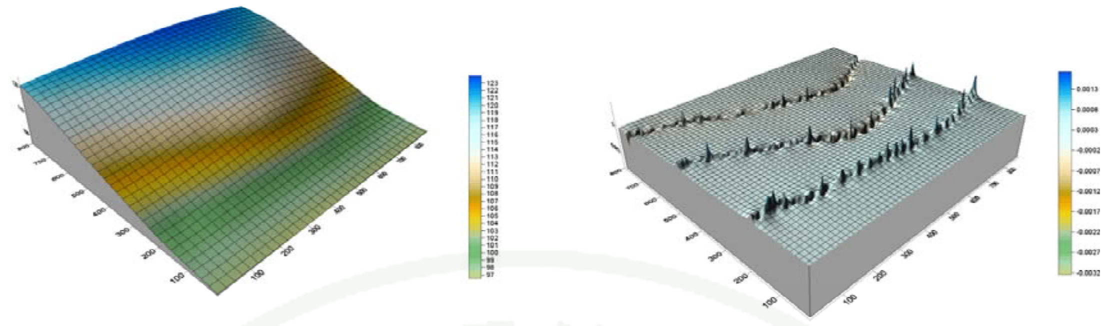
78	72	69	71	58	49
74	67	56	49	46	50
69	53	44	37	38	48
64	58	55	22	31	24
68	61	47	21	16	19
74	53	34	12	11	12

(c)

2	2	2	4	4	8
2	2	2	4	4	8
1	1	2	4	8	4
128	128	1	2	4	8
2	2	1	4	4	4
1	1	1	1	4	16

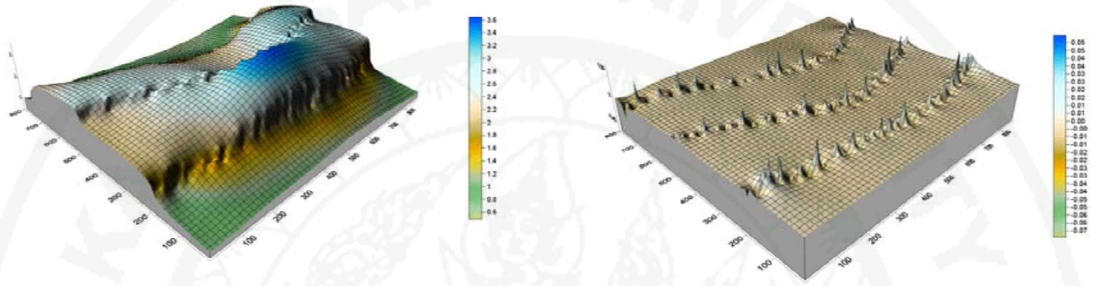
Figure 29 Assignment of flow directions using the D8 model. (a) elevations, (b) flow direction codes, (c) flow direction grid values, (d) symbolic representation of flow directions.

The terrain analysis results are shown in Figures30 to 34.



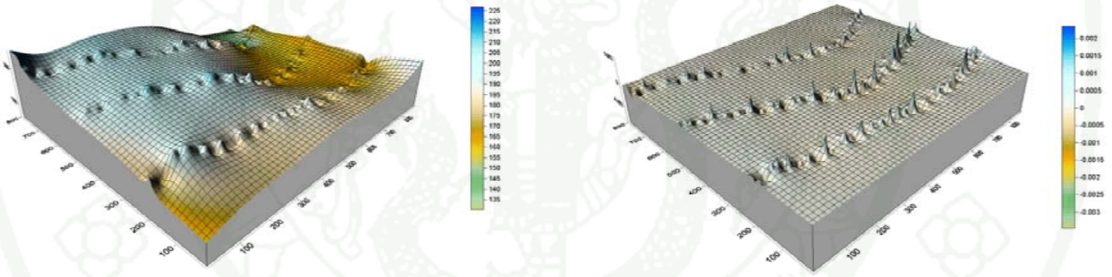
Terrain 3D

Profile Curvature



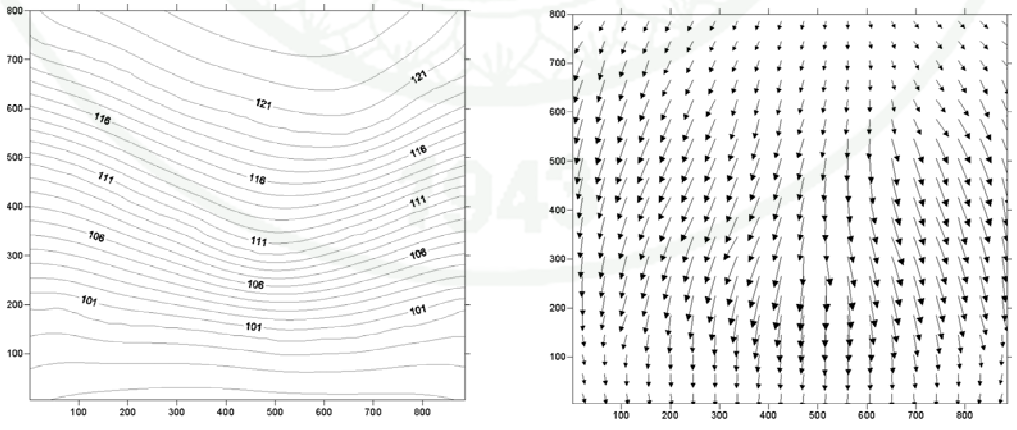
Terrain Slope

Plan Curvature



Terrain Aspect

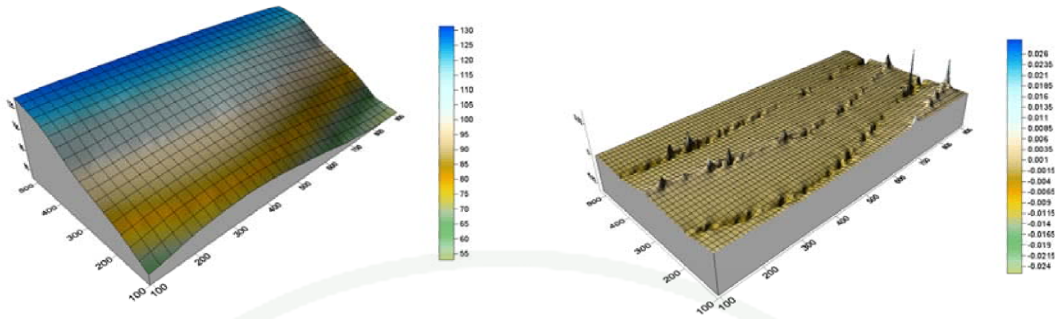
Tangential Curvature



Contour

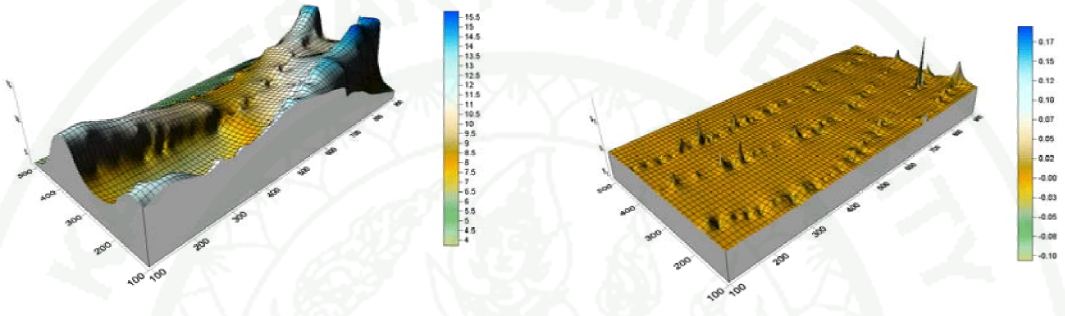
Single Flow Map

Figure 30 Terrain analysis results for a type I topography



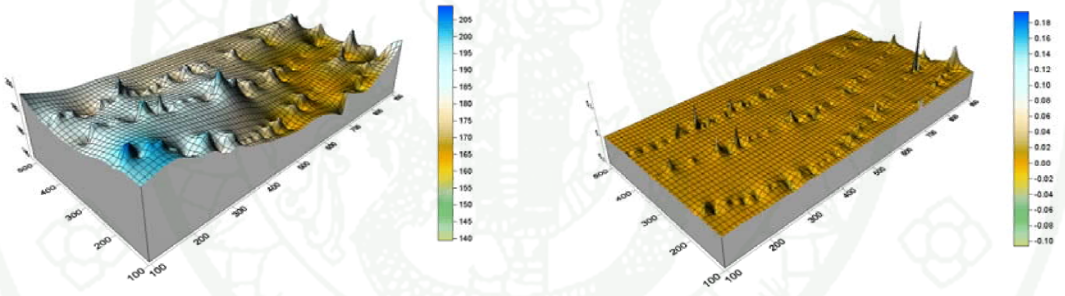
Terrain 3D

Profile Curvature



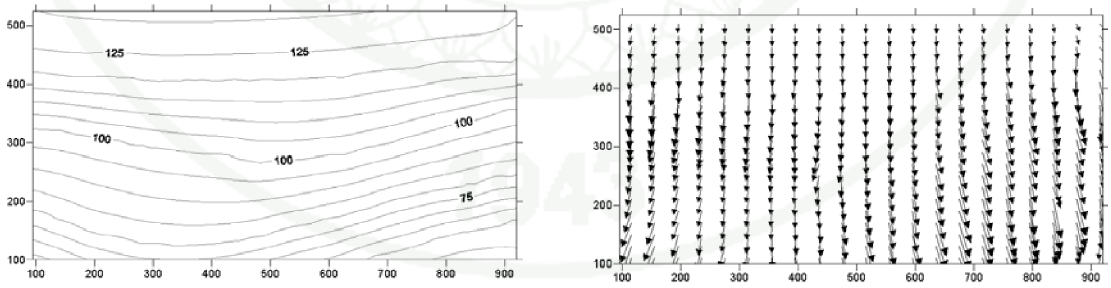
Terrain Slope

Plan Curvature



Terrain Aspect

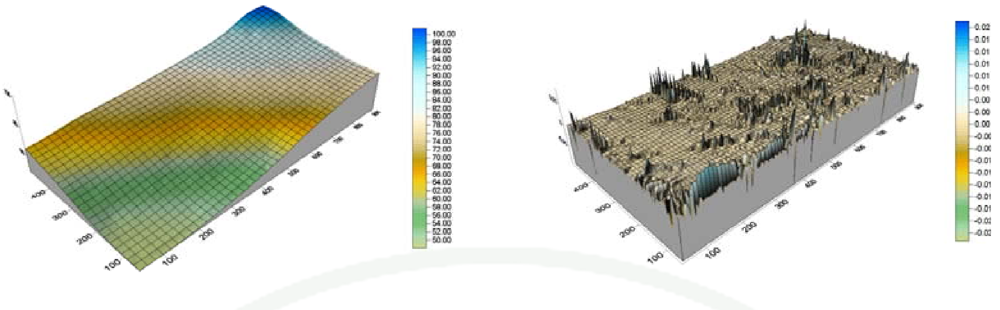
Tangential Curvature



Contour

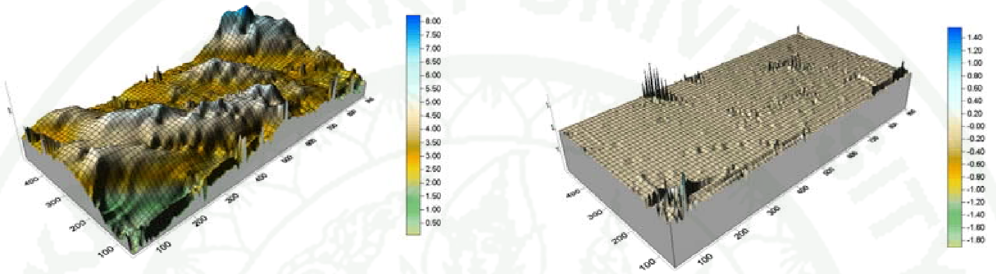
Single Flow Map

Figure 31 Terrain analysis results for a type II topography



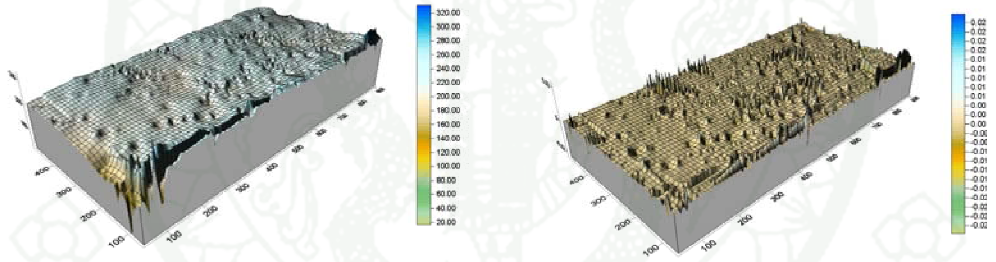
Terrain 3D

Profile Curvature



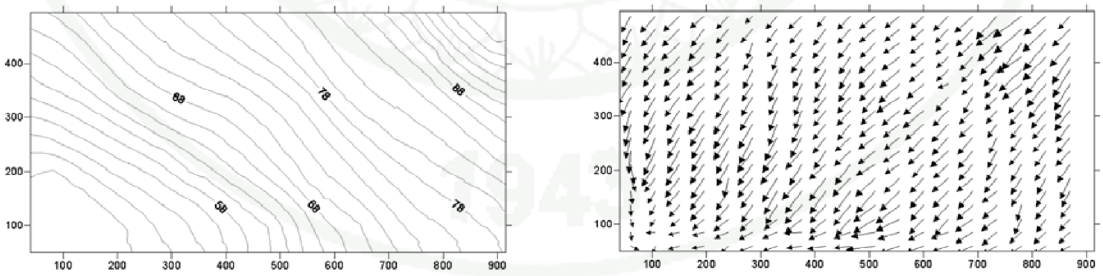
Terrain Slope

Plan Curvature



Terrain Aspect

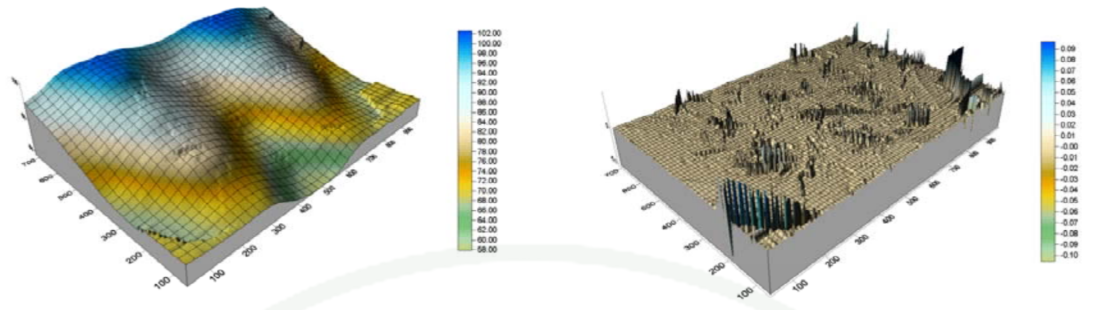
Tangential Curvature



Contour

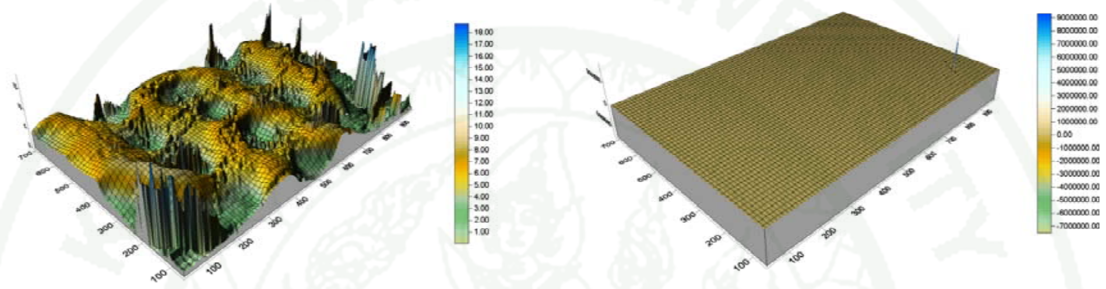
Single Flow Map

Figure 32 Terrain analysis results for a type III topography



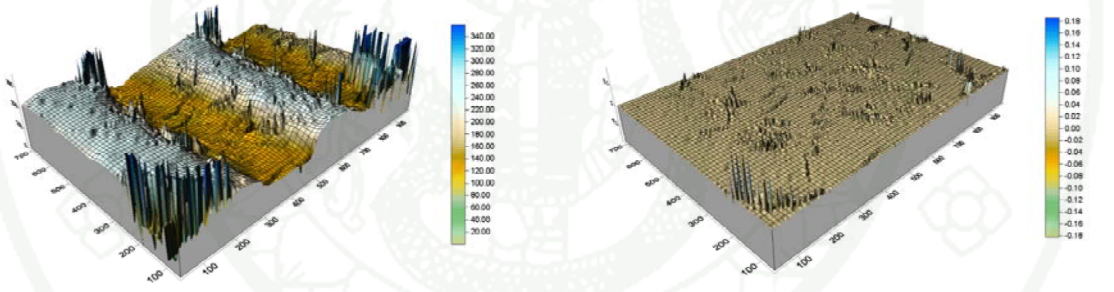
Terrain 3D

Profile Curvature



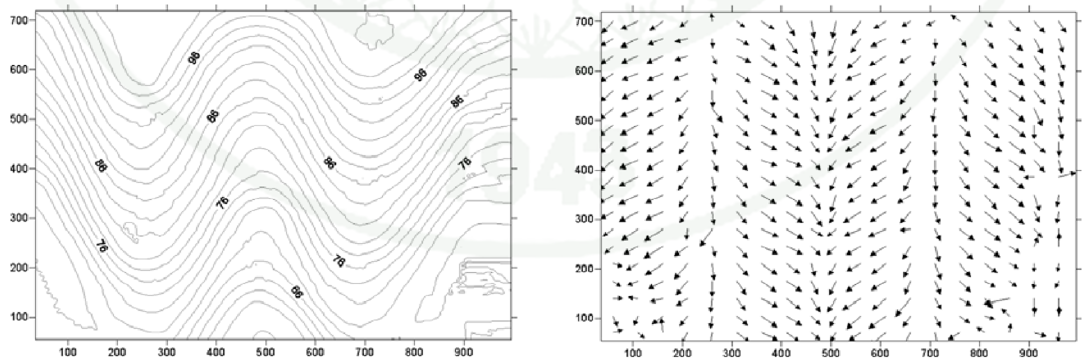
Terrain Slope

Plan Curvature



Terrain Aspect

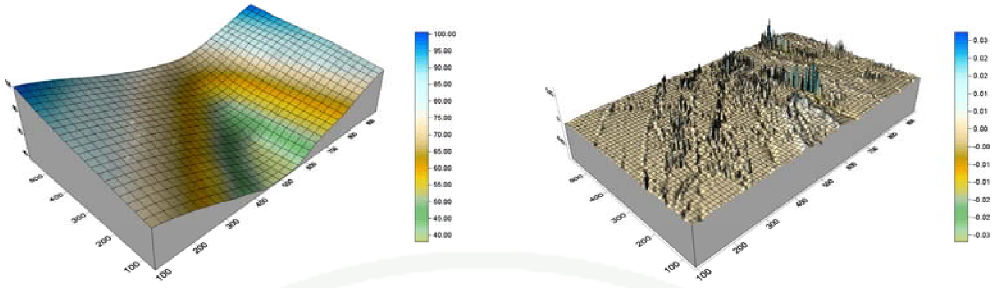
Tangential Curvature



Contour

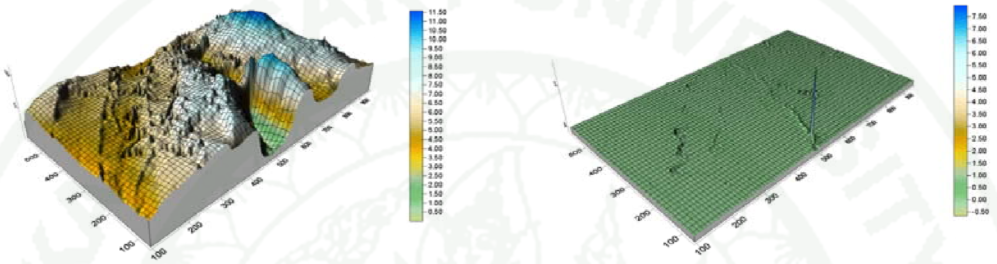
Single Flow Map

Figure 33 Terrain analysis results for a type IV topography



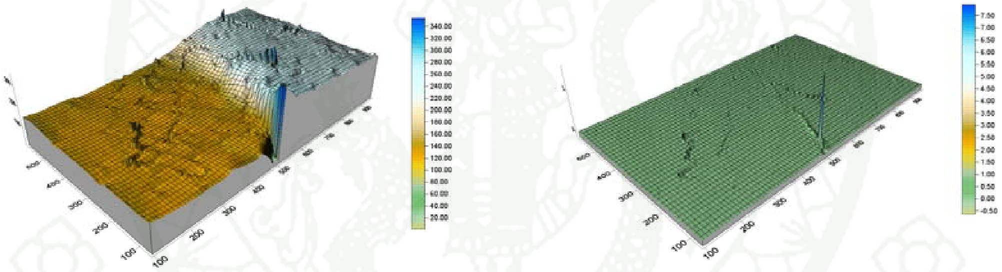
Terrain 3D

Profile Curvature



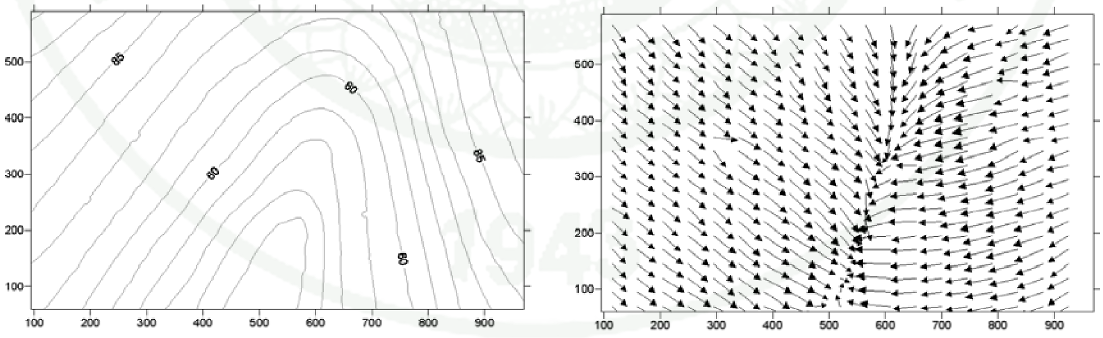
Terrain Slope

Plan Curvature



Terrain Aspect

Tangential Curvature



Contour

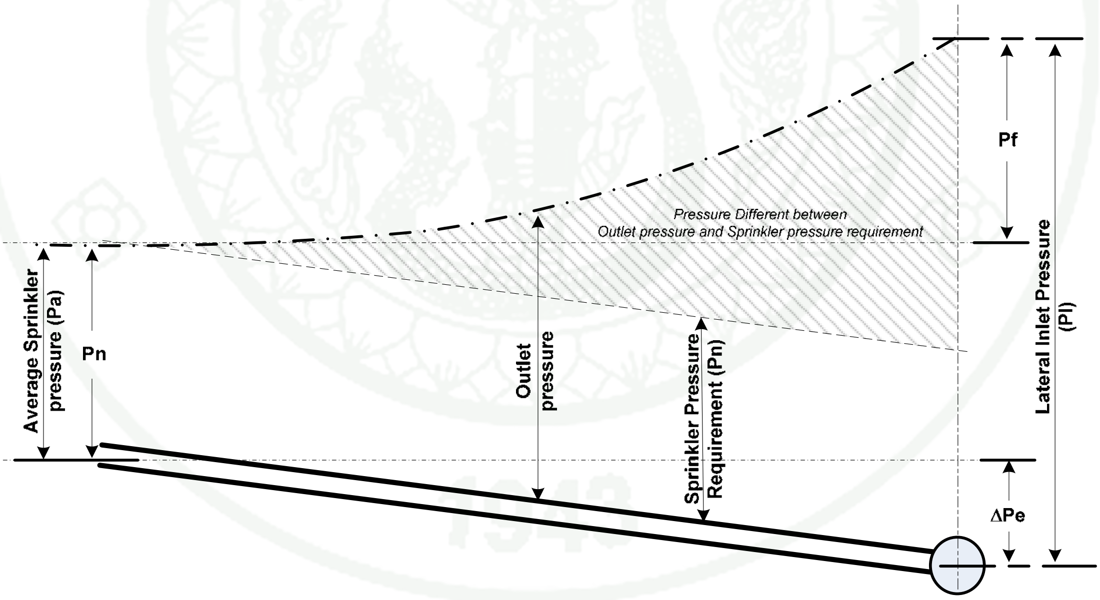
Single Flow Map

Figure 34 Terrain analysis results for a type V topography

c) Main-line Layout Design

Keller and Bliesner (2000)mention that “Main lines or sub-mains should usually run up and down the predominant land slope. Where laterals are down-slope, the mainline will often be located along a ridge, with laterals sloping downward on each side.” Ordinarily, mainline alignment is perpendicular to the laterals. Therefore, the mainline orientation could be uphill or downhill, as shown in Figures35 and 36.

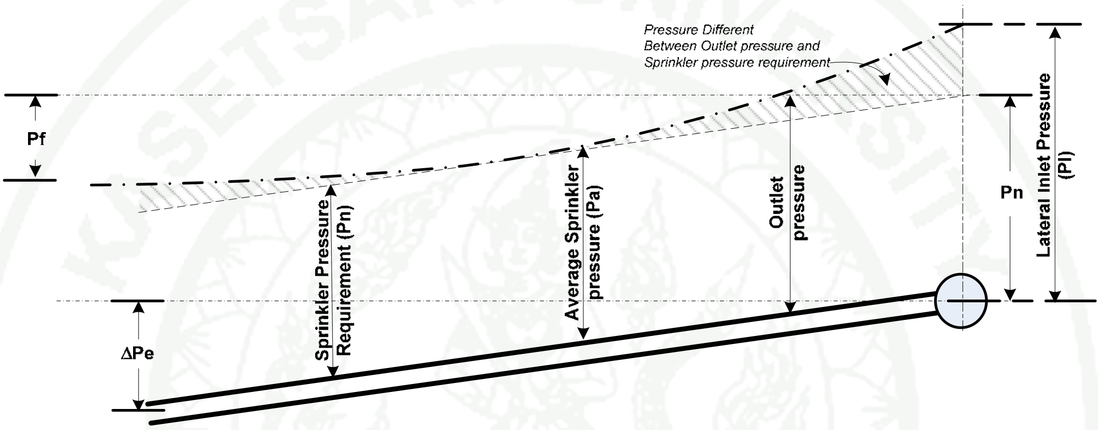
In the case of uphill laterals (Figure35), a traditional design criterion is that pressure loss due to pipe friction (P_f) may be equal to 20% of the average sprinkler pressure (P_a) minus the static pressure difference due to elevation (ΔP_e), which is the difference in elevation between the inlet and closed (downstream) ends of the lateral. ΔP_e is positive and increases as the elevation increases. The minimum pressure for sprinkler pressure requirement (P_n), occurs at closed end of the lateral pipe.



Lateral laid uphill: minimum pressure occurs at the closed end

Figure 35 Pressure relationship a lateral running uphill

In the case of uphill laterals (Figure36), the allowable of pressure loss due to pipe friction (P_f) is 20% of the average sprinkler pressure (P_a), plus the static pressure gain due to the decrease in elevation between the inlet and closed end of the lateral. ΔP_e for a downhill lateral is negative as it decreases in elevation along the pipeline. The minimum pressure for sprinkler pressure requirement (P_n) occurs at the point along the lateral where the pipe friction gradient equals the slope of the lateral.



Lateral laid downhill: minimum pressure is where the pipe friction gradient equals the slope.

Figure 36 Pressure relationships for a lateral running downhill

For these reasons, it can be concluded that downhill laterals are preferred over uphill laterals in terms of pressure distribution along the pipe. The cross section of each hill has one suitable mainline position. Similarly, in the valley case there are two suitable mainline positions because the valley is like the sides of two different hills. Keller and Bliesner (1990)conclude that a suitable mainline location, considering terrain and planted area, is as shown in Figures 37 to 41, and Table 4.

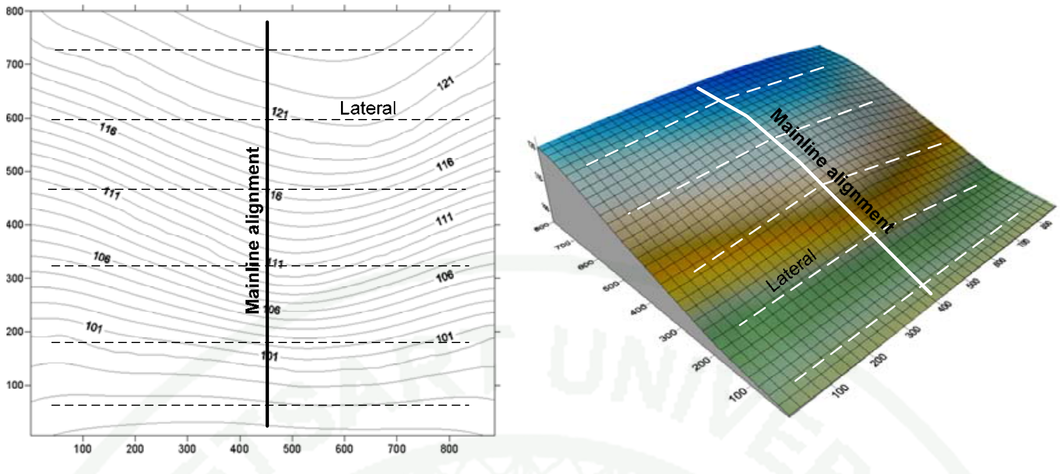


Figure 37 Mainline and lateral alignment for a type I topography

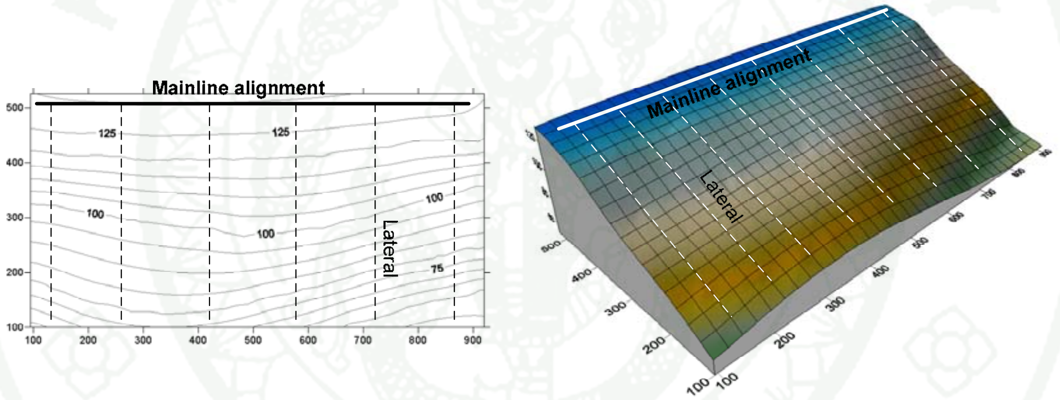


Figure 38 Mainline and lateral alignment for a type II topography

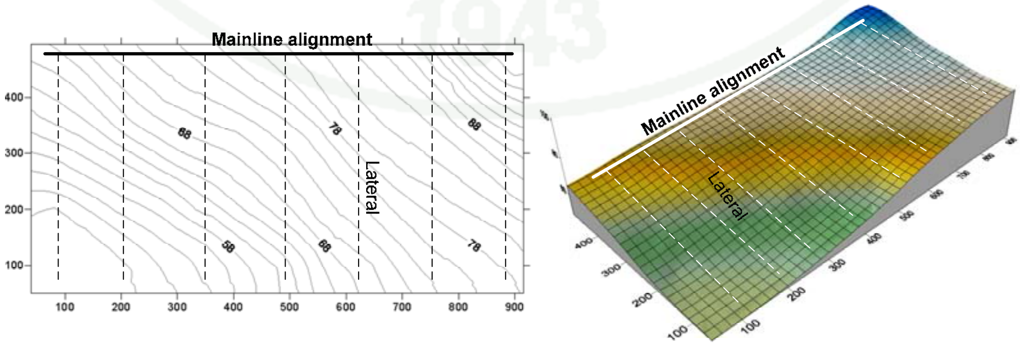


Figure 39 Mainline and lateral alignment for a type III topography

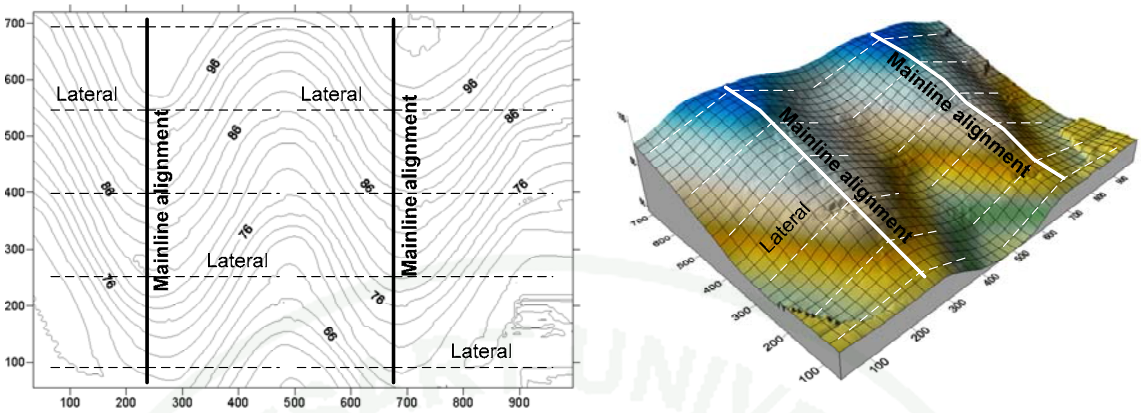


Figure40 Mainline and lateral alignment for a type IV topography

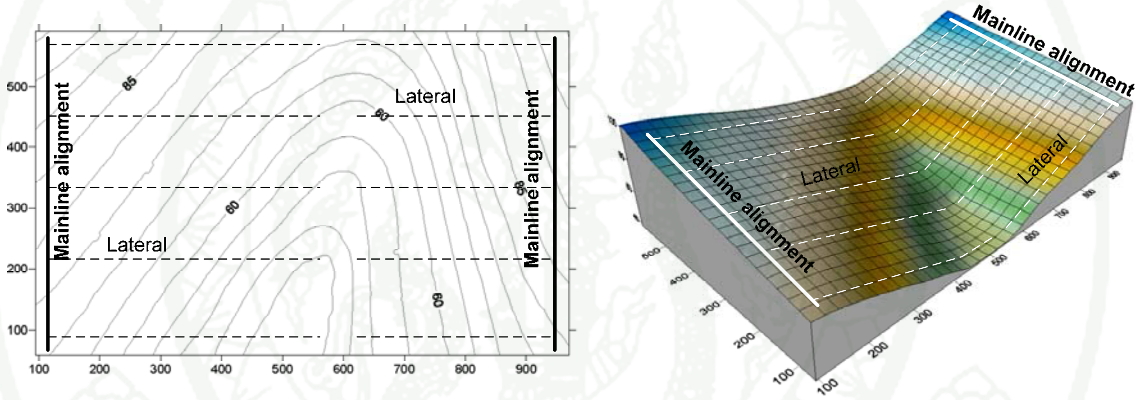
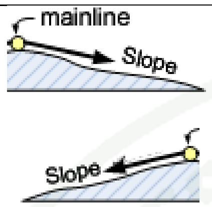
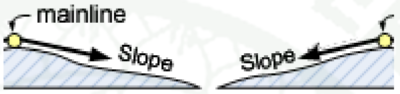
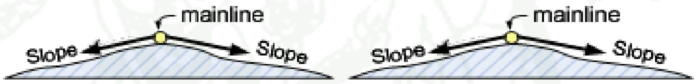


Figure 41 Mainline and lateral alignment for a type V topography

Table 4 Samples for suitable mainline location, considering field topography.

side	Number of Mainlines	
	1 Mainline	2 Mainline
1	 	
2	 	
3		
4		

d) Topographic Type Selection Criteria and Classification

The guide for mainline alignment location is based on five types of topography (Figure 42). The topography type can be determined using four cross section profiles, corresponding to the DEM sides of a rectangular planted area as shown in Figure42. Normally, the profile of a DEM side is not linear, but to evaluate a cross-section profile USUKU creates discrete imaginary lines that increase the length (L) from the first DEM grid point to the last DEM grid point. The imaginary lines are evaluated according to cross-section profiles and the coefficient of determination (R^2) is computed. The maximum length value (L) multiplied by the coefficient of determination (R^2) is a discrete point. If the calculated discrete point is less than the last DEM grid point, USUKU will create a new imaginary line that increases in length (L) from the discrete point to the last DEM grid, then checks it by the same process as shown in Figure 43.

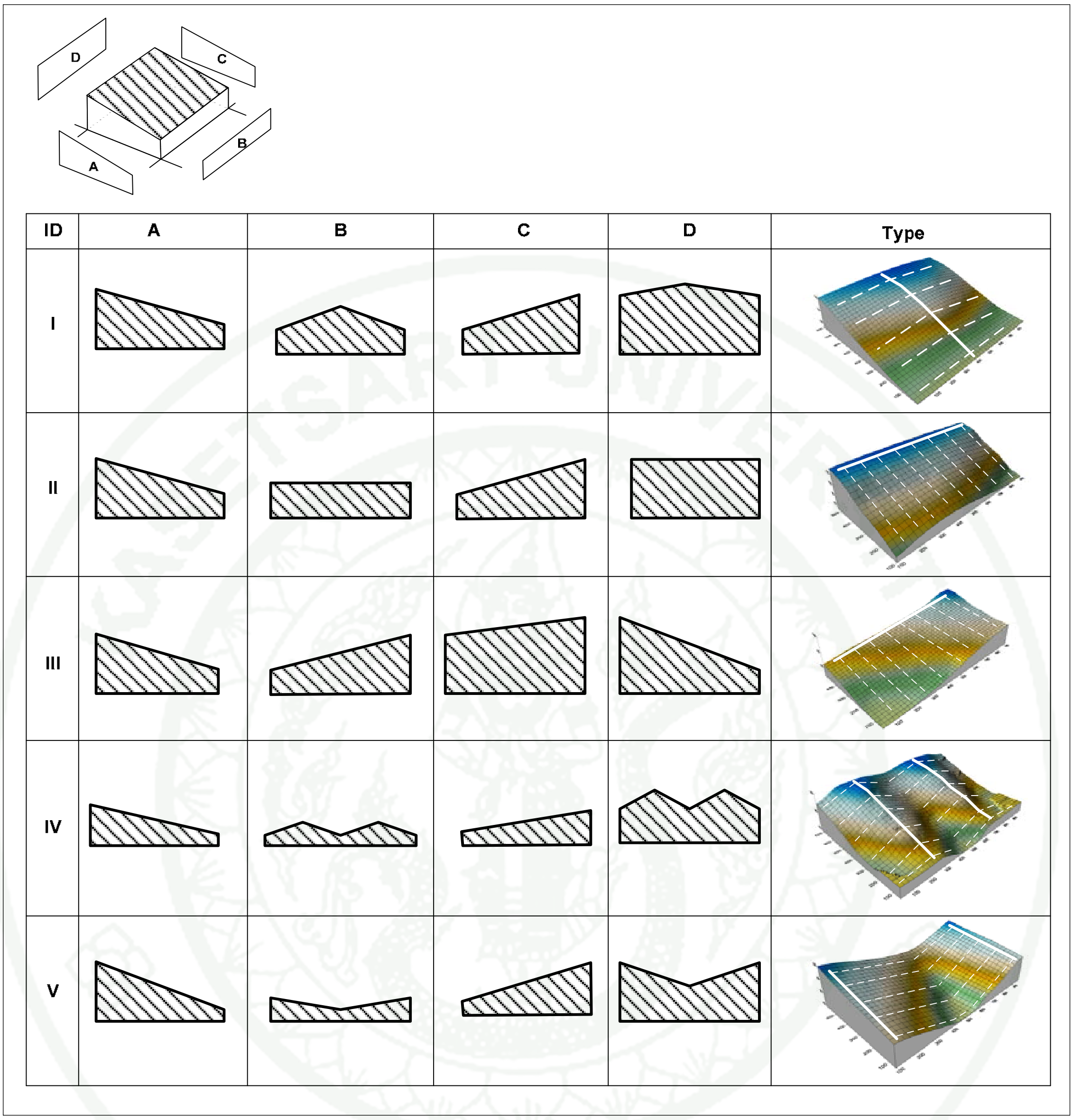
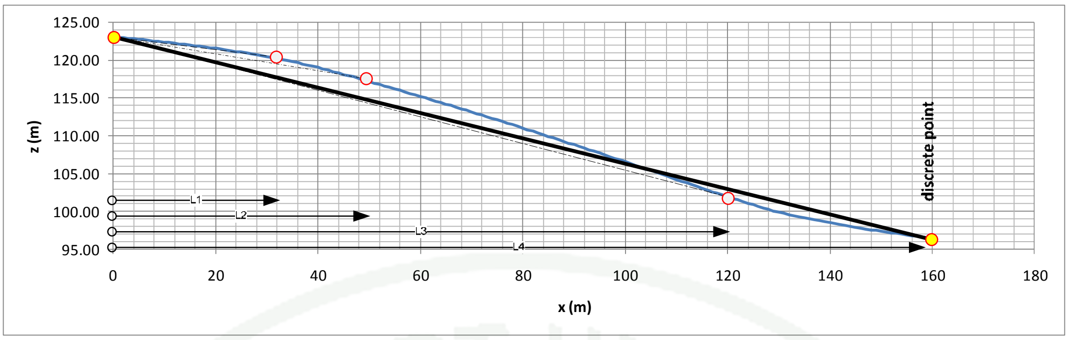
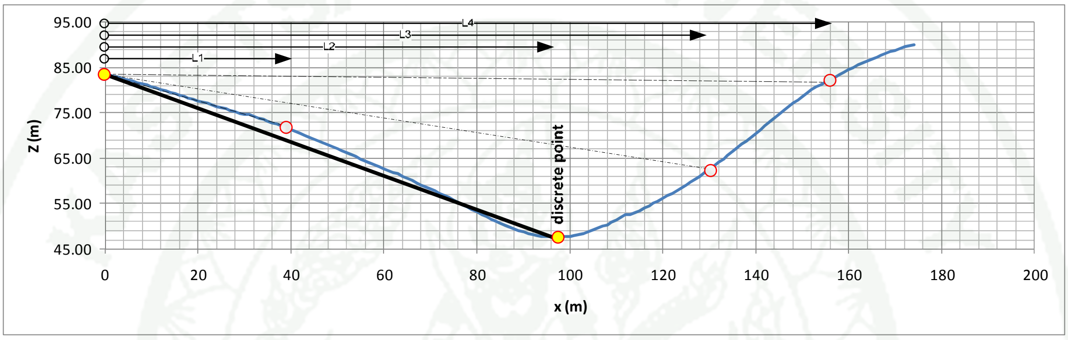


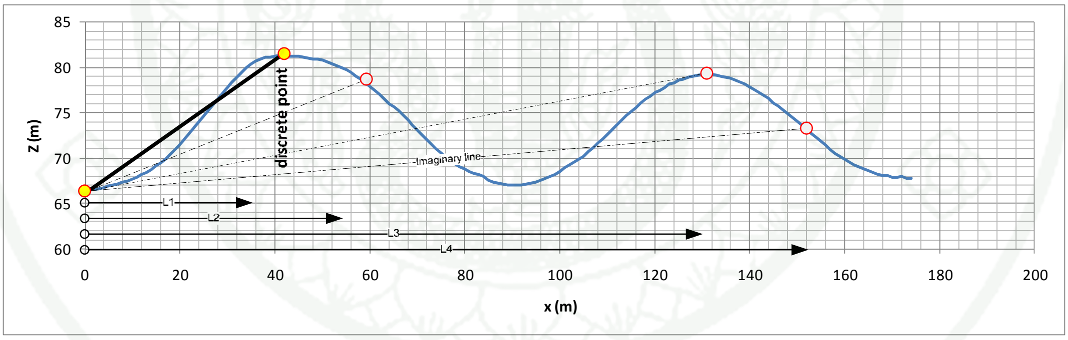
Figure 42 Topography type selection criteria



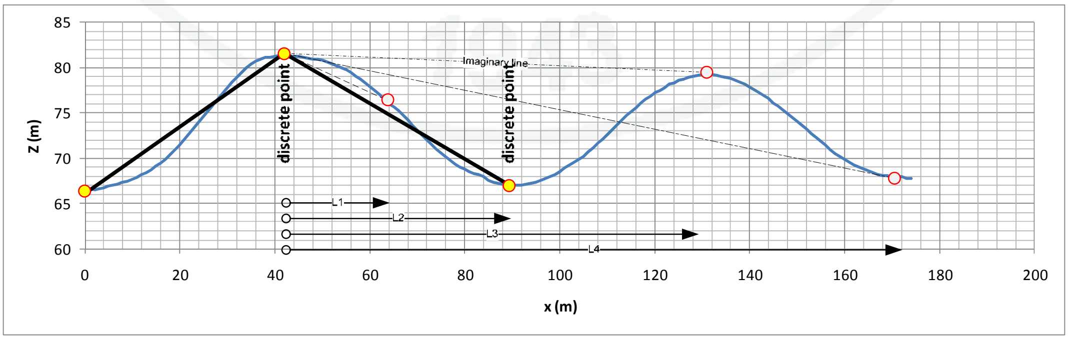
(a) Single plan on a cross section profile



(b) Double plan on a cross section profile (V shape)



(c) Multi plan on a cross section profile (first plan)



(d) Multi plan on a cross section profile (second plan)

Figure 43 Cross-section profile identification

2. Sprinkler Location

After USUKU has determined a mainline guide location and alignment from the topography analysis process, the next step is to obtain the sprinkler elevation data. The first data to be processed involve lateral alignment computations. The software is designed such that sprinkler laterals in USUKU are perpendicular to the mainline. Thus, the lateral alignment can be determined based on the concept of a line that touches the circle, and the sprinkler location on the lateral can be found as shown in Figures 44 and 45.

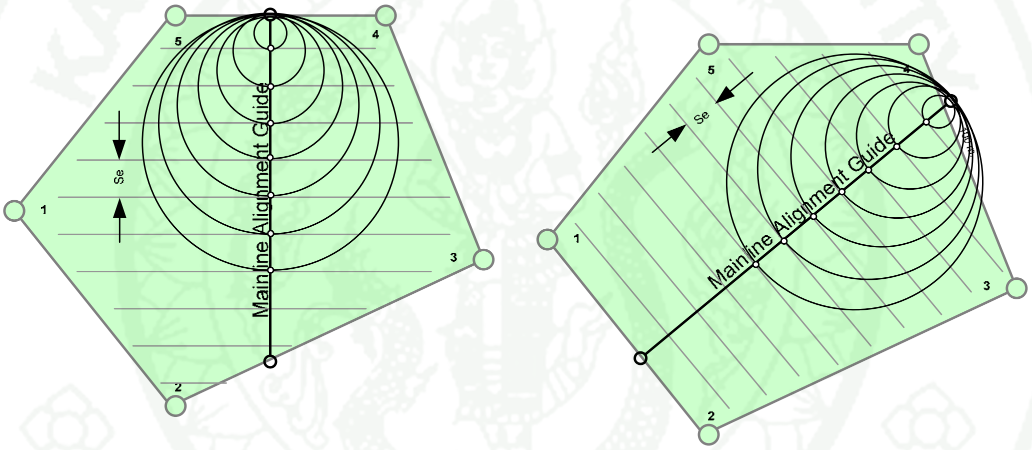


Figure 44 Lateral line alignment

..

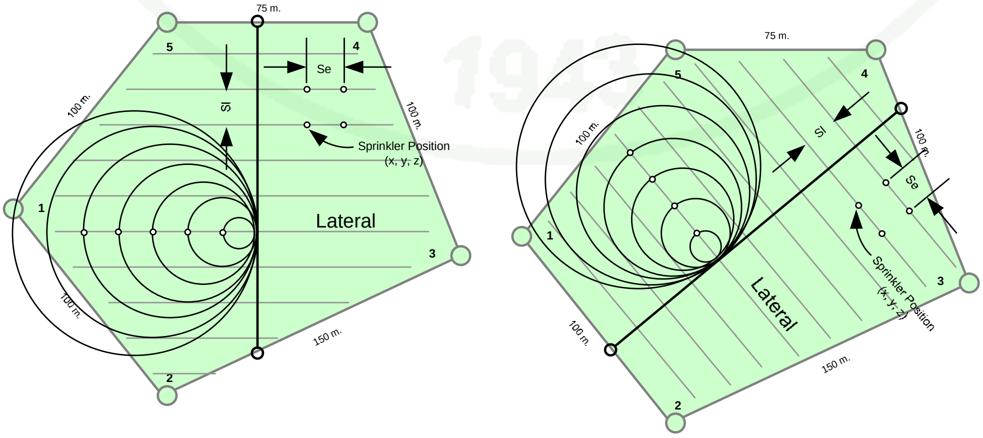


Figure 45 Sprinkler position

The 2^{nd} algorithm for sprinkler layout design is called the Point-In-Polygon Algorithm. This algorithm is determining for a point (x, y) inside or outside a 2D polygon bounded plane. This is necessary to separate the sprinkler positions in the planted area (Bourke 2007). Consider a polygon made up of N vertices (xi, yi) where iranges from 0 to N-1. The last vertex (xN, yN) is assumed to be the same as the first vertex (x0, y0), that is, the polygon is closed. To determine the status of a point (xp, yp) consider a horizontal ray emanating from (xp, yp) and to the right. If the number of times this ray intersects the line segments making up the polygon is even, then the point is outside the polygon. However, if the number of intersections is odd then the point (xp, yp) lies inside the polygon. Figure 46 shows the ray for some sample points and should make the technique clear.

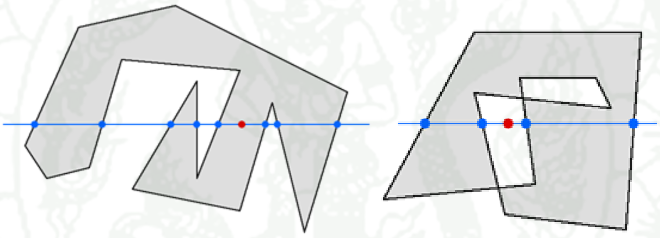


Figure 46 A ray intersecting a polygon to find whether a point is inside or outside the polygon

The solution is to compare each side of the polygon to the Y (vertical) coordinate of the test point, and compile a list of nodes, in which each node is a point where one side crosses the Y threshold of the test point. In this example, eight sides of the polygon cross the Y threshold, while the other six sides do not. Then, if there is an odd number of nodes on each side of the test point, it is inside the polygon; or, if there are even numbers of nodes on each side of the test point, then it is outside the polygon. In our example, there are five nodes to the left of the test point, and three nodes to the right. Since five and three are odd numbers, our test point is inside the polygon. This is useful for the designer to decide whether to use those values or not. If unsatisfied, the designer can adjust by rotating, or moving the grid to another position as shown in Figure 47.

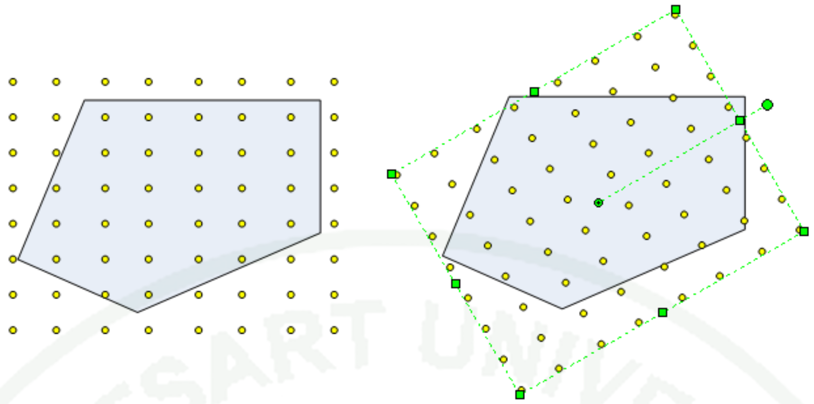


Figure 47 Sprinkler positioning distribution selection within the planted area by grid rotation

3. Initial link and Adjustment

The initial link and adjustment process is for initial and temporary pipe networking. At this point in the design process, USUKU contains a list of (x, y) points for sprinklers and junctions in a pipe network system which has a single mainline and multiple laterals. The initial pipe network is created by linking a point to adjacent points as shown in Figure 48. Then, Delaunay's algorithm (Delaunay 1934) is used to create the temporary links which are used to select the actual links in the pipe network layout process, as described in the next paragraph.

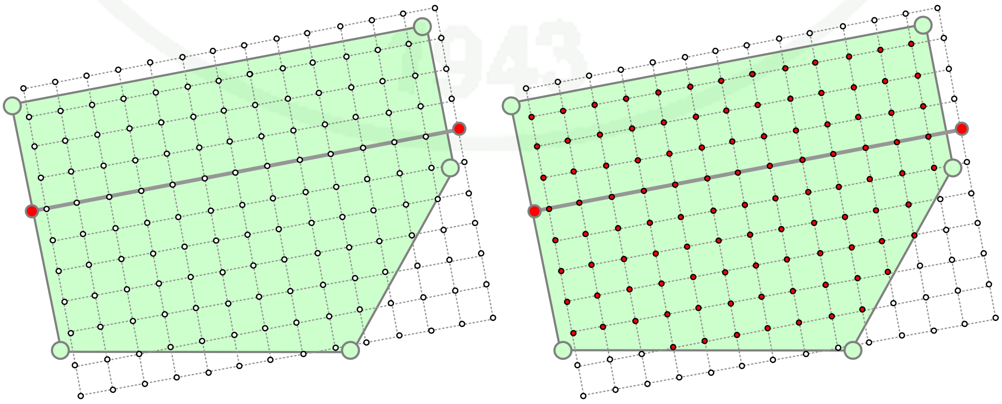


Figure 48 Initial pipe networking process

In case the mainline guide cannot cross from one side to the opposite site, the mainline guide must be modified. The steps to modify a mainline guide are: (1) delete a link of the guideline that is outside the planted boundary; (2) link all nodes that cannot fully connect to the network by adjacent nodes; and, (3) use only those nodes and links that are located inside the planted area, as shown in Figure 49.

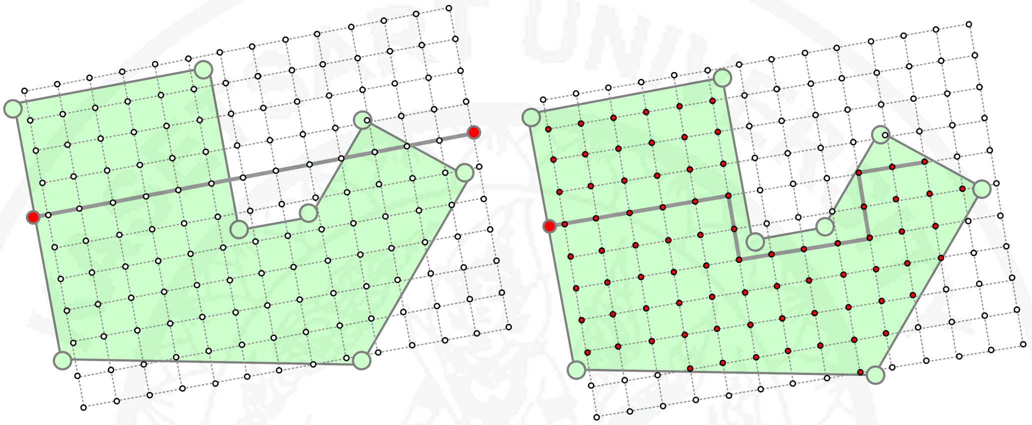
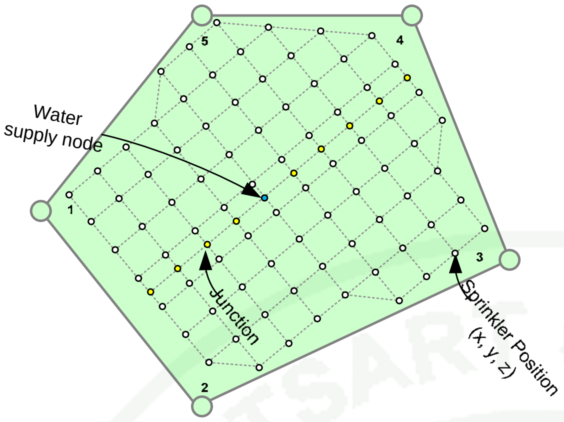


Figure 49 Initial pipe network and mainline guide modification process

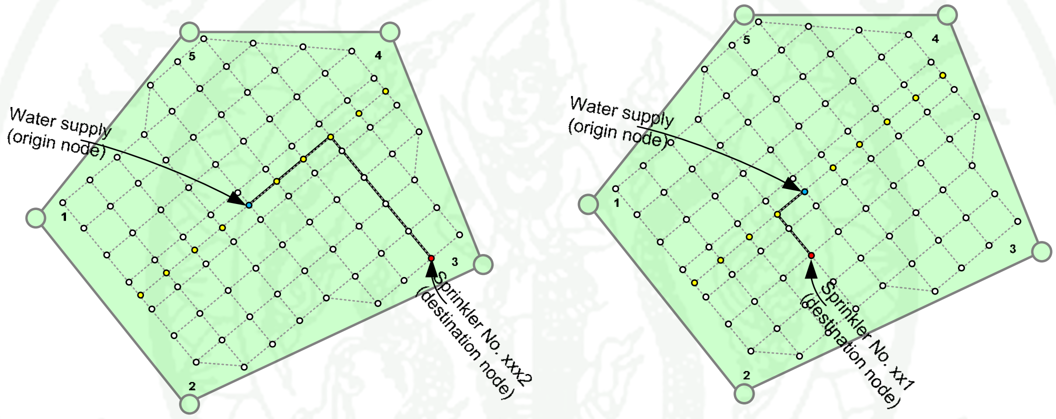
4. Flow Path Analysis

The water supply source node is an important node for the pipe layout algorithm. This is because the pipes that are used in linkages are selected by a shortest-path algorithm (Dijkstra's algorithm). The shortest-path algorithm is used to find the shortest distance from the water supply node to each sprinkler node (or position) in the initial network. Possible pipeline links (selected links) are shown as solid lines in Figure50.

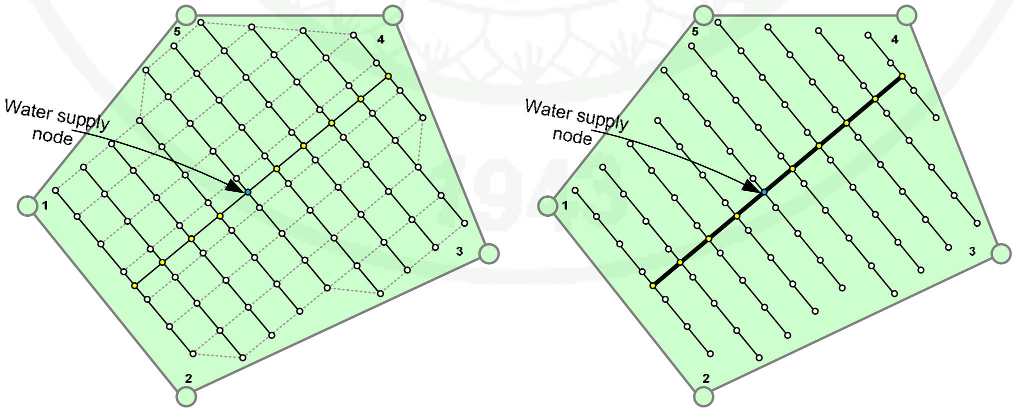
The result of one path is a list of links from the origin (water supply node) to the destination node (a given sprinkler node) so that the total path segments is equal to the number of sprinklers in the field. As this point USUKU has only a list of links of all paths, but without the required flow rates along the paths. USUKU estimates a rough flow path by assuming an operating pressure, such as 15 m of water head for all sprinklers in the field, and then calculating the sprinkler discharge ($q = k_d \sqrt{h}$), whereby flows are accumulated at all links along a given path, corresponding to one or more pipes in the network, as shown in Figure51. In practice, most links are found in multiple paths, meaning there are links that have a total calculated flow resulting from multiple paths which overlap at that location. USUKU considers each link in the list from all paths, and then accumulates the flow along the path to a flow link as shown in Figure52. The total flow at a link is used to define a maximum and minimum range of pipe sizes (diameters) by applying a specified velocity limit range.



(a) Initial pipe network and water supply node

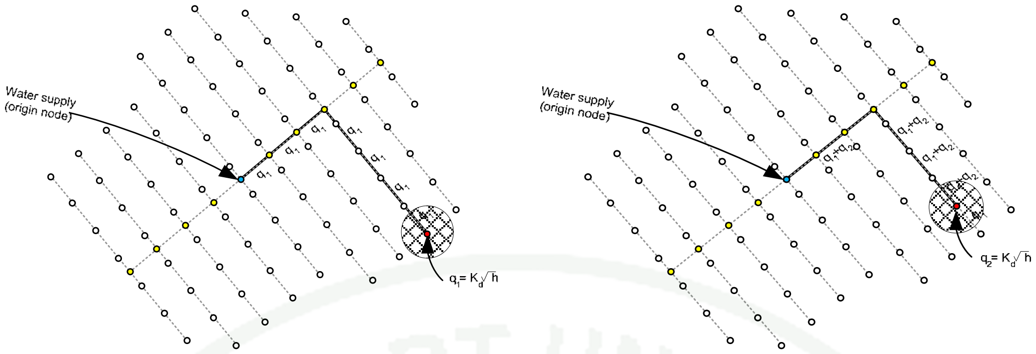


(b) A sample of shortest-path result for selecting a link from water supply node (origin node) to a selected node (destination node).

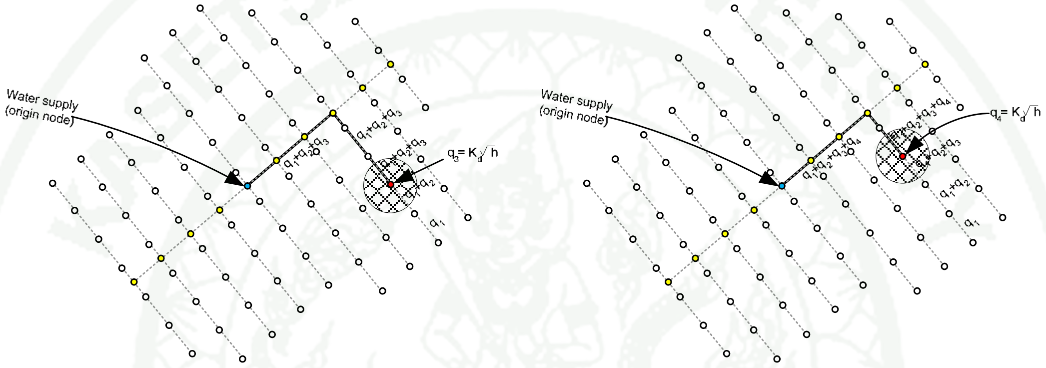


(c) Summary of used links that are selected by the shortest-path algorithm from the origin to all destination nodes or pipe layout (solid line)

Figure 50 Pipe layout selection process



(a) Flow of path 1 ($\sum Q= q_1$) (b) Flow of path 2 ($\sum Q= q_1+q_2$)



(c) Flow of path 3 ($\sum Q= q_1+ q_2+q_3$) (d) Flow of path 2 ($\sum Q= q_1+q_2+q_3+q_4$)

Figure 51 Accumulation of flow rates along a path

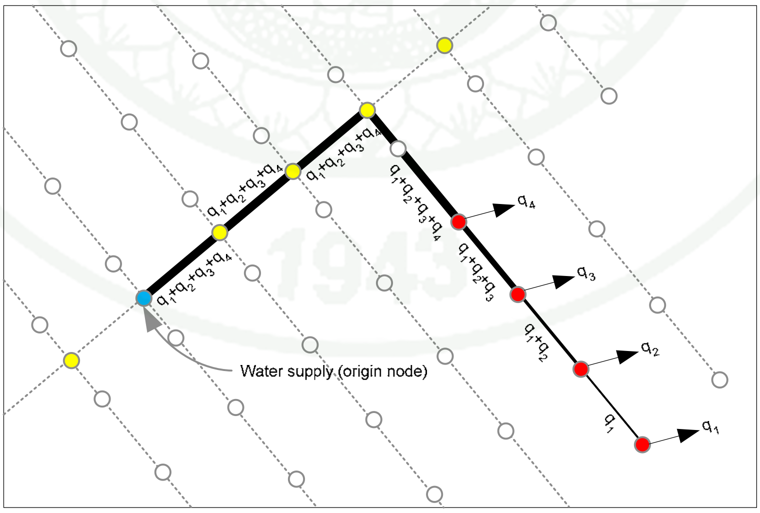
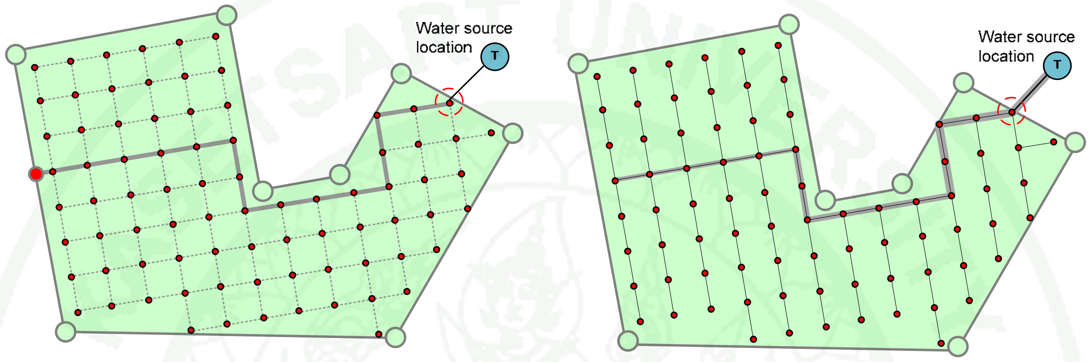
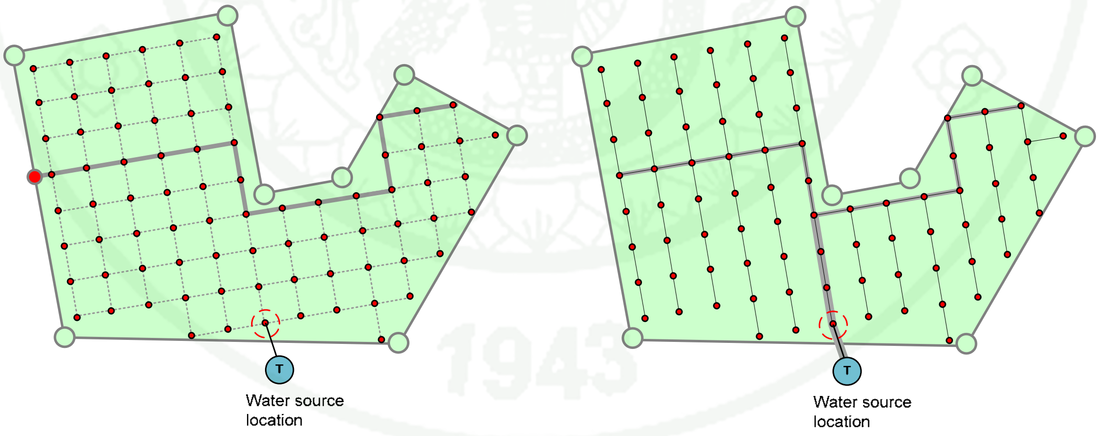


Figure 52 Flow accumulation concept at a link

If a given water supply location is changed, USUKU will find new flow paths for the pipe layout as shown in Figure53. In this case all pipe locations for a given layout are not different, but the pipe size in the layout is changed. The reason for this is that the flow path from any node to the water supply is potentially changed, and then the flow accumulates differently and the pipe size will change as well.



(A) Water supply source location is connected at the end of the mainline guide location



(B) The water supply source location is connected at some node in the network

Figure 53 Flow path and flow accumulation concepts

C. Pipe Hydraulic Model

The irrigation pipe hydraulic model for this research is based on a gravity-fed model in which there is a fixed pressure head at the water supply (i.e. no pumping). A gravity-fed irrigation system is an effective way to supply water for a sprinkler irrigation system when there is sufficient elevation difference between the water source and the irrigated area; that is, the water source is above the planted area. The basic system is very simple, consisting of an elevated reservoir or tank with a pipe coming out of the bottom that feeds water into a sprinkler irrigation system that is controlled either manually or with a very efficient timer that controls the irrigations according to crop water requirements. For the gravity-fed system, the pressure head available due to elevation differences between the topography must be equal to the friction losses. The model is based on the Bernoulli and Hazen William equations, and the model formulation schematic is shown in Figure54.

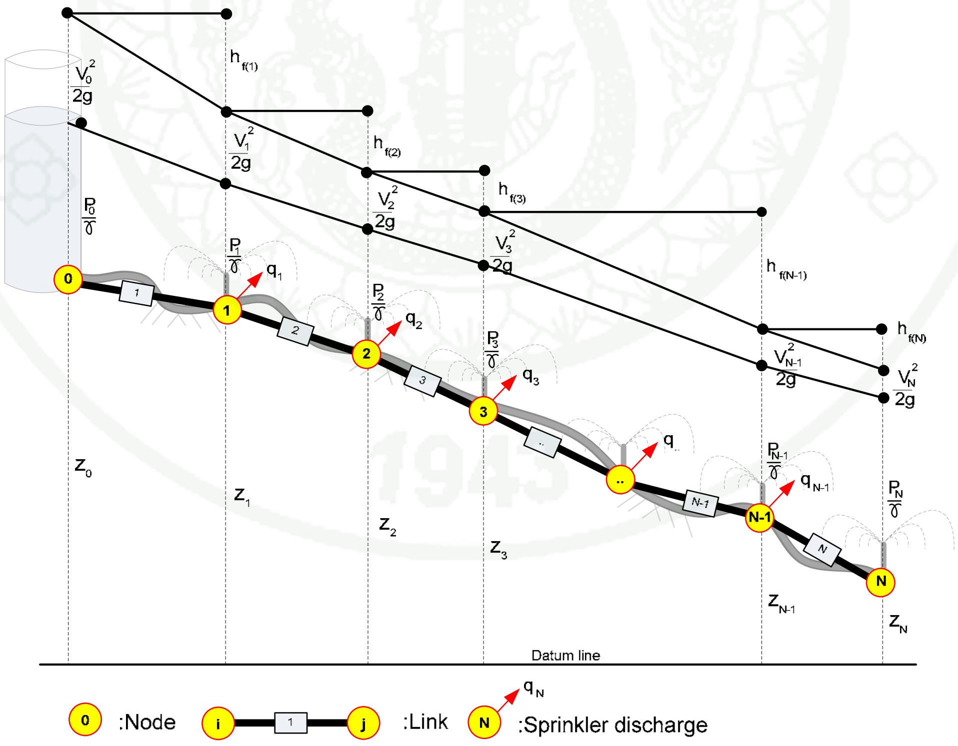


Figure 54 Pipe hydraulic model formulation schematic

1. Hydraulic Model Assumptions

a) Water level of the tank or reservoir does not change.

b) The equation is for a known inlet head (H_0), sprinkler spacing, field topography, sprinkler discharge coefficient (k_d), riser height (h_r), pipe diameter (D) and pipe material (C factor).

c) Friction loss is based on the Hazen-Williams equation.

d) There are three node types: sprinkler location, water source location, and pipe junction.

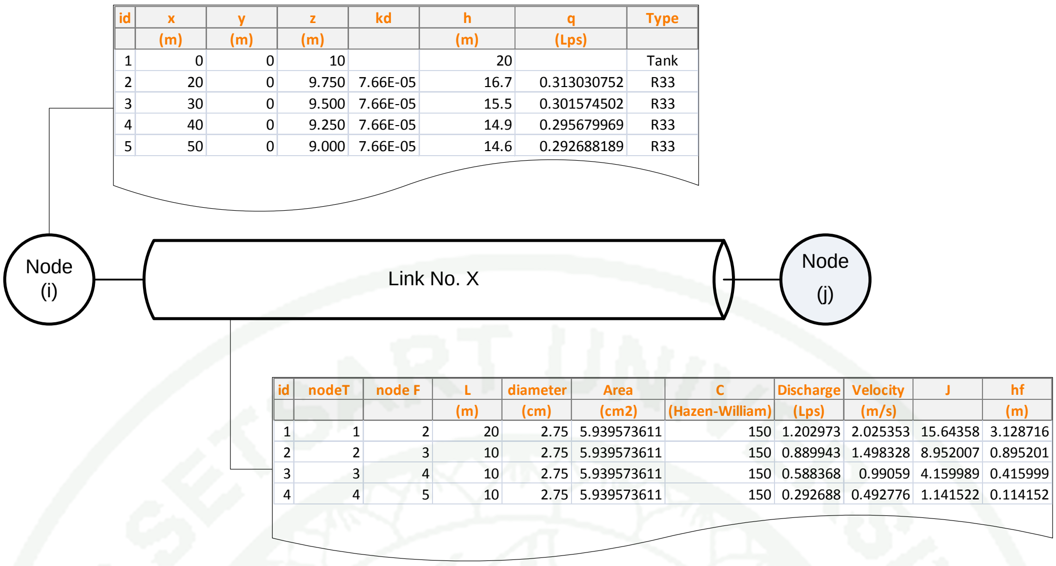
e) Nodal properties are:

- *id* = node number
- *x* = UTM E (m)
  (Note UTM is Universal Transverse Mercator coordinate system)
- *y* = UTM N (m)
- *z* = elevation (m above MSL)
- K_d = sprinkler discharge coefficient
- *h* = nodal pressure (m)
- *q* = *Sprinkler discharge (cms)*
- *Type* = *Nodal type*

f) Link is pipe that connects between two nodes.

- *id* = Link number
- *NodeF* = Begin node No. (Node From)
- *NodeT* = End node No. (Node To)
- *L* = Pipe length (m)
- *diameter* = Pipe diameter (cm)
- *Area* = Pipe diameter (cm^2)
- *C* = pipe material (C factor)
- *Discharge* = pipe flow (L/s)
- *Velocity* = pipe velocity (m/s)
- *J* = Head loss factor (m/100)
- *Hf* = Head loss (m)

A schematic diagram of a node and the pipe data structure is shown in Figure55.



id	x	y	z	kd	h	q	Type
	(m)	(m)	(m)		(m)	(Lps)	
1	0	0	10		20		Tank
2	20	0	9.750	7.66E-05	16.7	0.313030752	R33
3	30	0	9.500	7.66E-05	15.5	0.301574502	R33
4	40	0	9.250	7.66E-05	14.9	0.295679969	R33
5	50	0	9.000	7.66E-05	14.6	0.292688189	R33

id	nodeT	node F	L	diameter	Area	C	Discharge	Velocity	J	hf
			(m)	(cm)	(cm2)	(Hazen-William)	(Lps)	(m/s)		(m)
1	1	2	20	2.75	5.939573611	150	1.202973	2.025353	15.64358	3.128716
2	2	3	10	2.75	5.939573611	150	0.889943	1.498328	8.952007	0.895201
3	3	4	10	2.75	5.939573611	150	0.588368	0.99059	4.159989	0.415999
4	4	5	10	2.75	5.939573611	150	0.292688	0.492776	1.141522	0.114152

Figure 55 Node and pipe data structure

2. Model formulation

a) Friction loss

Friction head loss (m per 100 m pipe) in water pipes can be estimated using the empirical Hazen-Williams equation as shown in Eq. 16.

$$h_f = \frac{JL}{100} \qquad (16)$$

Where:

$$J = 16.42(10)^6 \left\{\frac{Q}{C}\right\}^{1.852} D^{-4.87} \qquad (17)$$

and Q is the pipe flow (L/s); D is the pipe diameter (cm); J is the friction loss gradient (m/100 m); and, h_f is the friction head loss (m). Therefore, ignoring minor losses, the friction loss in the lateral pipe between two adjacent sprinklers is:

$$h_f = \frac{JL}{100} = 16.42(10)^4 \left\{\frac{Q}{C}\right\}^{1.852} D^{-4.87} L \qquad (18)$$

b) Sprinkler discharge

Sprinkler discharge (q) is a function of sprinkler pressure as shown in Eq. 19 for a simple orifice.

$$q = k_d \sqrt{h} \qquad (19)$$

where q is the sprinkler discharge (L/s); k_d is an empirical coefficient; and, h is the pressure head (m) at the sprinkler.

3. Gravity-fed Model Development

A schematic of the gravity-fed model as shown in Figure56 consists of nodes and links. Node number zero is the water source node (tank or reservoir). The number of nodes and links are equal, but nodes begin with zero and links begin with one. A circle represents a node and the thick black line is a link or a pipe in the irrigation system. The system has a fixed head at the source (tank), pipe properties (diameter, material “C”, length, connecting nodes (to and from), node elevation, node type (sprinkler, junction, tank), sprinkler properties (riser height, sprinkler type, discharge coefficient k_d) and node coordinates (x, y).

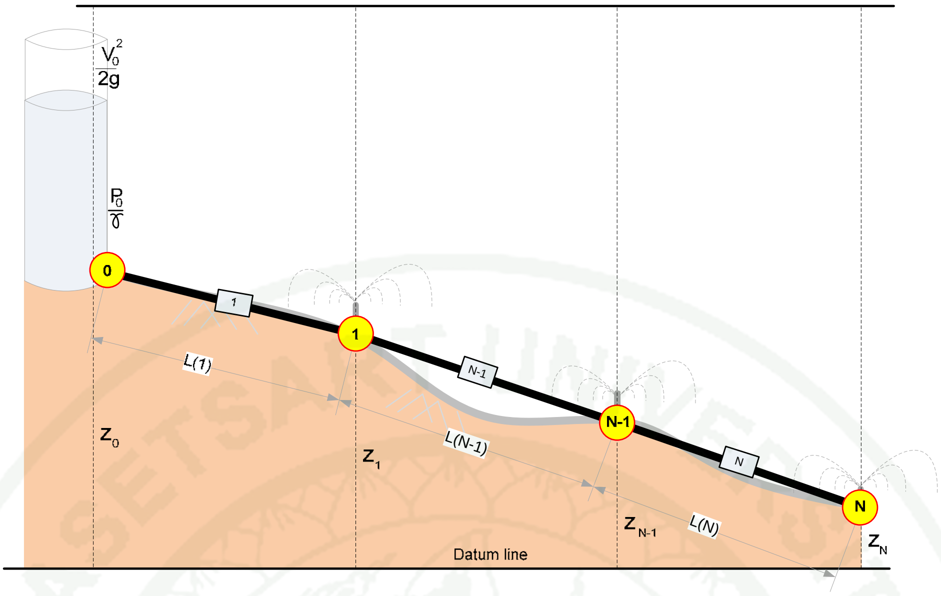


Figure 56 Schematic of the gravity-fed model

The modeling steps begin by assuming the water head or pressure at the last node of a lateral, and then calculating in the upstream direction to the first node (node zero) to compare with the head at the water supply. It is an iterative process, converging when the specified and calculated heads at the source are equal. The calculation steps are (Figure 57):

Step1: Assume pressure at the last node of lateral

Step2: Compute the last sprinkler discharge $q = k_d\sqrt{h}$ (cms)

Step3: Sum the sprinkler flow to pipe that upstream connecting (Q_n) (cms)

Step4: Get elevation head and riser height (Z_n) (m)

Step5: Calculate pressure head $\frac{P}{\gamma}$ (m)

Step6: Calculate the velocity head $\frac{V^2}{2g}$ (m)

Step7: Compute the head loss (m)

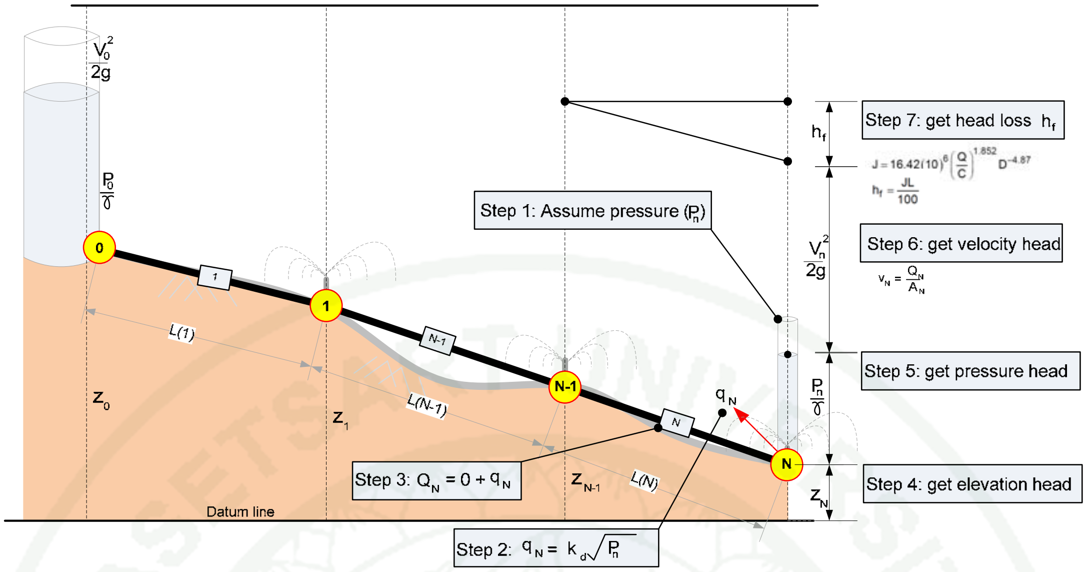


Figure 57 Gravity-fed hydraulic analysis to determine pressures and discharges

After calculating the hydraulic properties at the downstream node (node to or node-k) of a link (Link-n), the next step is to compute the hydraulic properties at the upstream node of the link (node from or node-j). Then, the hydraulic results of each upstream node are the hydraulic properties of each downstream node (node to or node-j) of the link (link n-1) that have an identical node name (node-j), as shown in Figure 58.

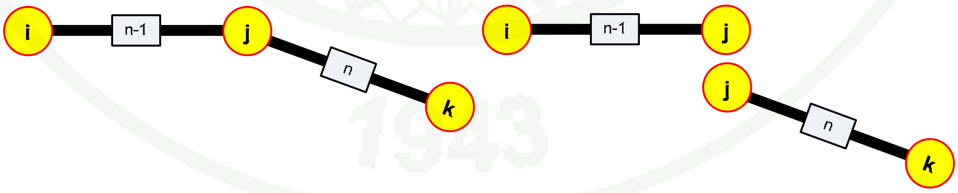


Figure 58 Two links connecting at node j

The calculation steps (Figure 59) for hydraulic properties at an upstream node are:

Step1: Determine the elevation difference *(ΔE)* between node from and Node to (m)

Step2: Compute the upstream pressure head $Hn\text{-}1=\Delta E + hfn + Hn$ *(m)*

Step3: Compute the last sprinkler discharge $q = k_d\sqrt{h}$ (cms)

Step4: Sum up the sprinkler flows in the pipe at this location *(Qn) (cms)*

Step5: Determine the elevation head and riser head *(Zn) (m)*

Step6: Determine the pressure head $\frac{P}{\gamma}$ (m)

Step7: Determine the velocity head $\frac{V^2}{2g}$ (m)

Step8: Compute the hydraulic head loss (m)

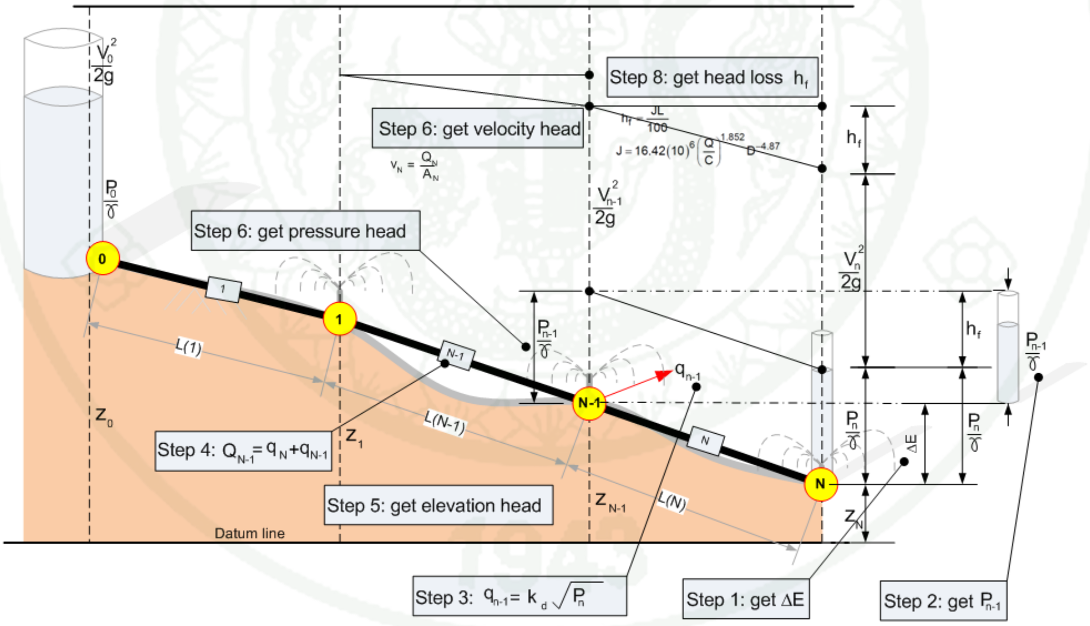


Figure 59 Gravity-fed computation process

The calculation loop moves upstream through the pressurized system to determine hydraulic properties at each successive upstream node until arriving at node zero (the source node). Finally, the computed pressure or head and source head are compared as shown in Figure60. The absolute error between calculated and specified source heads is used to adjust the new end node pressure and to re-compute again until the error is acceptably small. All computational processes are shown in pseudo code form in Figure61.

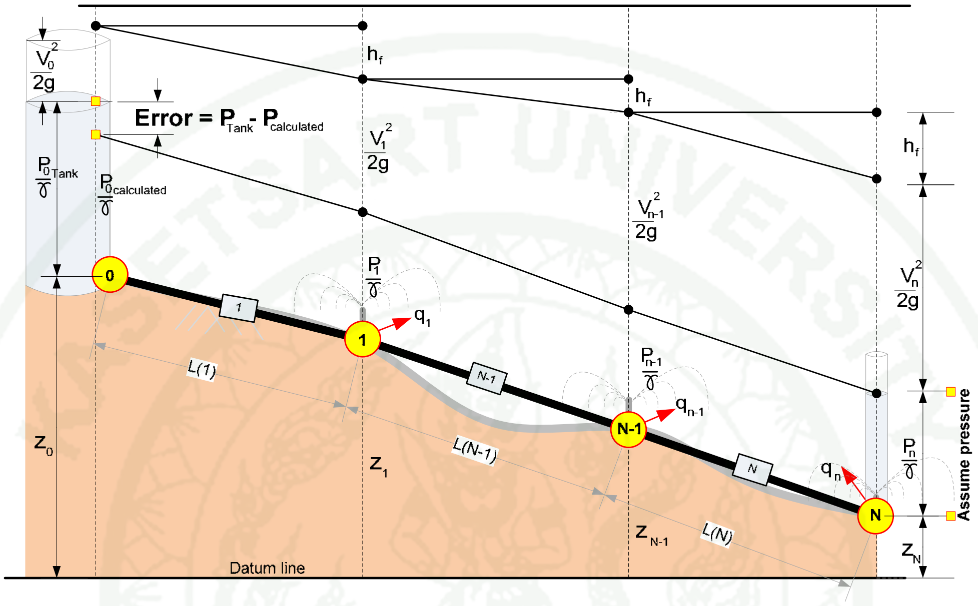


Figure 60 Comparison of computed and specified pressure heads at the source node

```
// Assume H at oulet
Head = H_assume
  For i = nNode To 0
      //Assign nodal head.
       nodes(i).h = head
      //Get different elevation between 2 nodes.
       DeltaE = nodes(i).z - nodes(i - 1).z
      //Nozzle flow.
       nodes(i).q = nodes(i).kd * head ^ 0.5
      //Sum Link Flow.
       Links(i).Discharge = Links(i+1).Discharge +
       nodes(i).q
      //Head loss computation
       Links(i).J = Function_J()
      Links(i).Velocity = Function_V()
       hf = Links(i).L  * Links(i).J / 100
      Links(i).hf = hf
       hf += sprinkMinorLoss * Links(i).Velocity ^ 2/(2g)
      //Update head for upstream node
       head = head + hf + DeltaE
  Next
   Return Abs(H upstream - head) //Return H different.
```

Figure 61 Pseudo code for the gravity-fed calculation process

4. Golden section Search

In fact, the pressure at the end node of a lateral is between zero (end node level) and the source elevation plus Δ*E* (water source level). This allows bracketing of the solution and guarantees a successful conclusion to the calculations. The error results of gravity-fed from that range are plotted as shown in Figure62. The solution of the absolute-value graph is the point at which the error is nearly zero.

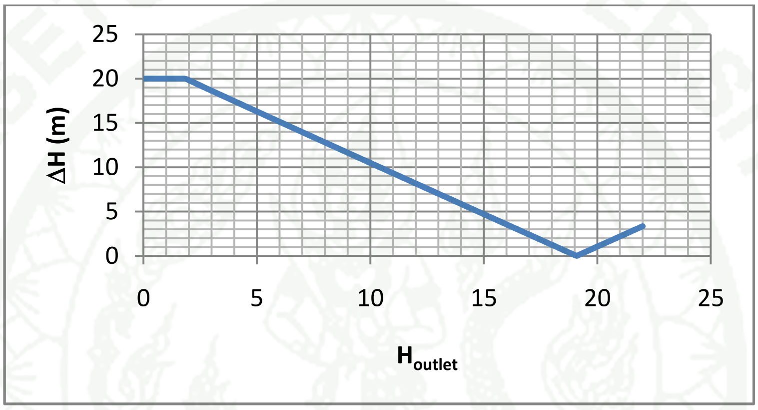


Figure 62 Relationship between outlet head and absolute error at water source point

The golden section search algorithm is a technique for finding a solution in the searching boundary (head between zero to head at the tank +Δ*E*). The objective function for searching is minimizing the error evaluation value. In the golden section search process, two lines (a and b) will be added to the graph as shown in Figure63(a). The distance between points a and b correspond to either thelower or upper boundary, and is related to the Fibonacci number, or in other words, the golden ratio. The next step is to consider the evaluated value of three adjacent points (lower limit to point (a) or point (b) to the upper limit), and then select a new search boundary (lower or upper) as shown in Figure63 (b). This process is repeated until the solution is found.

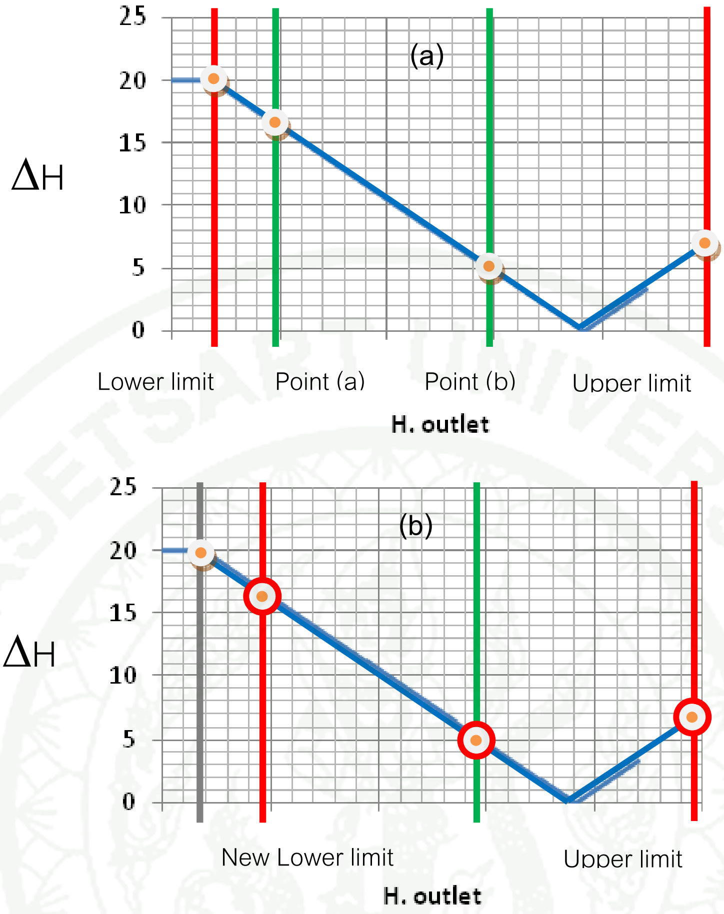


Figure 63 Golden section search technique

D. Irrigation Water Application Uniformity

The depth of water application is obtained from water application rate overlapping. The water overlapping depends on sprinkler properties (type, pressure) and layout (sprinkler location). To perform the overlapping, USUKU uses three GIS layers for computing the water application. Two layers are used for input data. The first layer is “Sprinkler.shp” which is used for providing the data of all sprinklers in a project area, such as sprinkler type, nozzle pressure, and sprinkler location. The second layer is “PlantedArea.shp”, which is used to limit the overlapping area (Figure 64). USUKU computes a water overlap for all simulated locations in the planted area. The last layer is the grid layer (Uniformity.acs), which saves the overlap data as shown in Figure 65.

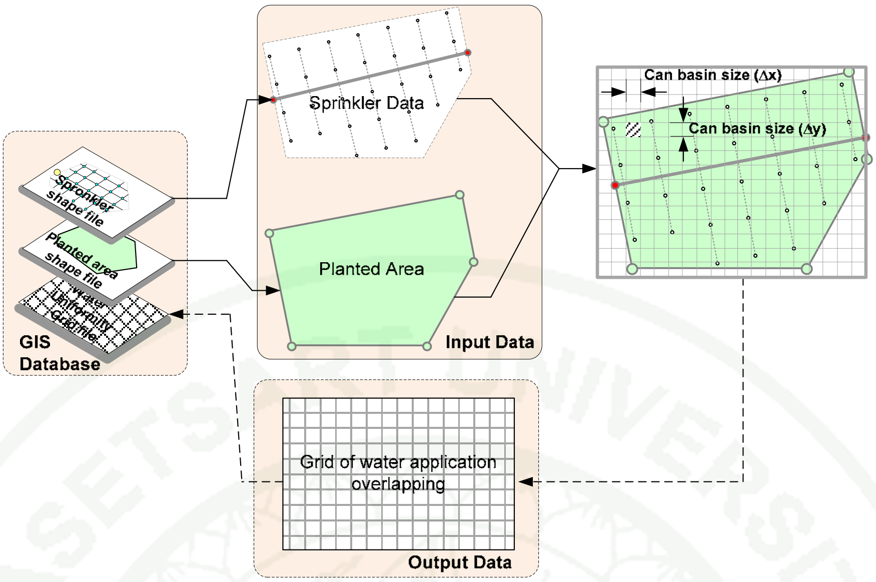


Figure 64 Water overlapping process

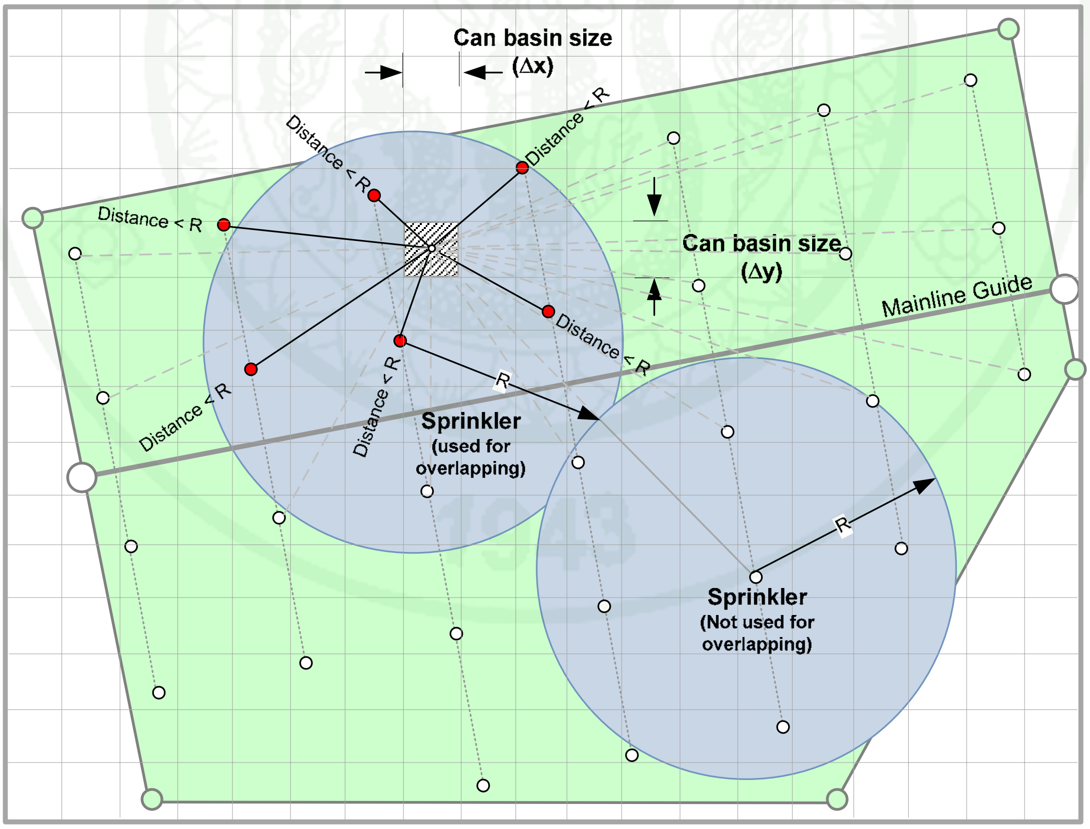


Figure 65 Illustration of water overlapping calculations

The evaluation of sprinkler irrigation uniformity is done with a grid of overlapped data. Grid or catch-can data are used to calculate application uniformity coefficients. USUKU provides two evaluation criteria (CU and DU) for evaluating the layout's water application uniformity.

CU is expressed in equation form as:

$$CU = 100\left[1 - \frac{\sum_{i=1}^{n}\left|V_i - \overline{V}\right|}{\sum_{i=1}^{n} V_i}\right] \tag{20}$$

where

V_i = an individual catch can measurement;

$\overline{V}$ = average volume of application from all catch-can measurements.

The low-quarter distribution uniformity is also often used to express sprinkler irrigation uniformity (DU):

$$DU = \frac{\overline{V_{lq}}}{\overline{V}} \tag{21}$$

where

$\overline{V_{lq}}$ = average of the lowest one-fourth of catch-can measurements

$\overline{V}$ = average depth of application over all catch-can measurements.

4. System Integration

To integrate the various modules of the USUKU model, MapWindow is used to provide a developer toolkit for the Windows platform and a fully functional mapping application (Ames 2008). The MapWindow project started in 1998 at the Utah Water Research Lab (UWRL) at Utah State University. UWRL created the core MapWinGIS.ocx component. MapWindow GIS is distributed as an open-source application under the Mozilla Public License, and it can be reprogrammed to perform different or specialized tasks. Other plug-insare also available to expand compatibility and functionality. The application is built upon Microsoft .NET technology. The MapWindow framework (Figure66.) consists of the main MapWindow application, Core Components, and plug-ins.

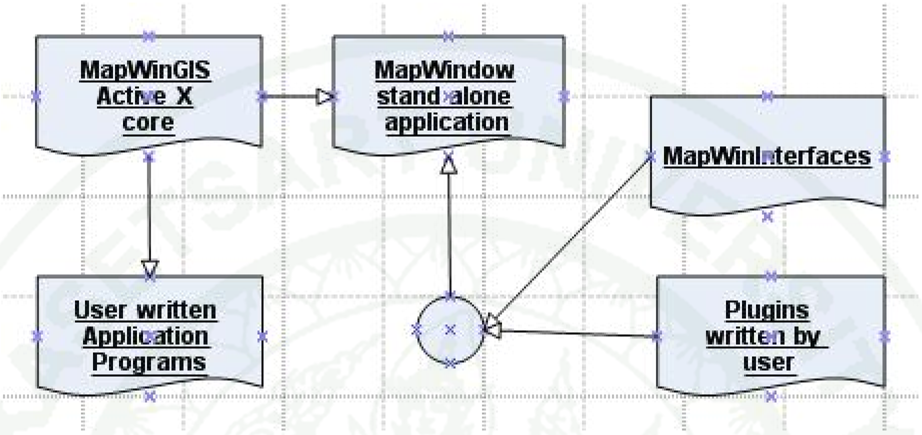


Figure 66 The MapWindow framework

- Main MapWindow Application (stand-alone GIS application)

This is the central interface for MapWindow. From here, it is possible to view data elements such as Shapefiles and ESRI Grids file.

- Core Components

These are the components which operate underneath MapWindow. The two main components are MapWinGIS and MapWinInterfaces.

- MapWinGIS (basis for MapWindow and user written GIS applications)

This is an ActiveX control which may be placed into any project in any programming language that supports ActiveX. This is the main map component if user wanted to write a program that displayed shape data, for example, this control could be used for the display portion of a program.

- MapWinInterfaces (part of MapWindow)

Also called the "Plugin Interface", this is a DLL file which will allow a person to write their own plug-ins to the main MapWindow application. This may be done from any programming language which supports the creation and use of Windows Dynamic Link Libraries (DLLs).

- Plug-ins (user can written extensions to MapWindow)

These are specialized tools written to interact with the main MapWindow application. Where MapWindow is mainly a data viewing tool, the real power of MapWindow comes in the form of custom-developed plug-ins.

The MapWindow open-source GIS platform is a system which contains a great deal of simple,and straight-forward GIS functionality which overall is enough to meet the needs of many users. However, the greatest aspect of MapWindow is that it is not limited purely to the base functionality provided, but instead allows a fully extensible plug-in interface that allows users to customize their MapWindow functionality to meet their custom needs with some fairly simple .NET code. For this reason, the MapWindow plug-in was developed for integrating all components of the design of sprinkler irrigation pipe layouts (USUKU). The plug-in was developed in VB .NET and compiled as a dynamic link library (DLL file). MapWindow can connect to the DLL, or plug-in, with interfacing functions, and data and event commands.

RESULTS AND DISCUSSION

1. Introduction

The USUKU model described herein is a MapWindow (Ames 2010) plug-in for the design of sprinkler irrigation pipe layouts. The plug-in was developed in VB .NET and compiled as a dynamic link library (DLL file). MapWindow can connect to the DLL, or plug-in, with interfacing functions, and data and event commands. The results of the model development are described below for the following major components:

- MapWindow Overview
- Irrigation Sprinkler Water Application Uniformity
- Pipe Hydraulic Model
- Sprinkler Layout Design

Although it is a single plug-in to MapWindow, it involves the components given above which perform various sophisticated functions and includes several thousand lines of code.

2. MapWindow Overview

The MapWindow GIS desktop application is a free, open source, standards-based standalone software package that can be used to view and edit GIS data in many file formats. The user can download the installation software from http://www.MapWindow.org/download.php. After installation, MapWindow will appear as shown in Figure 67.

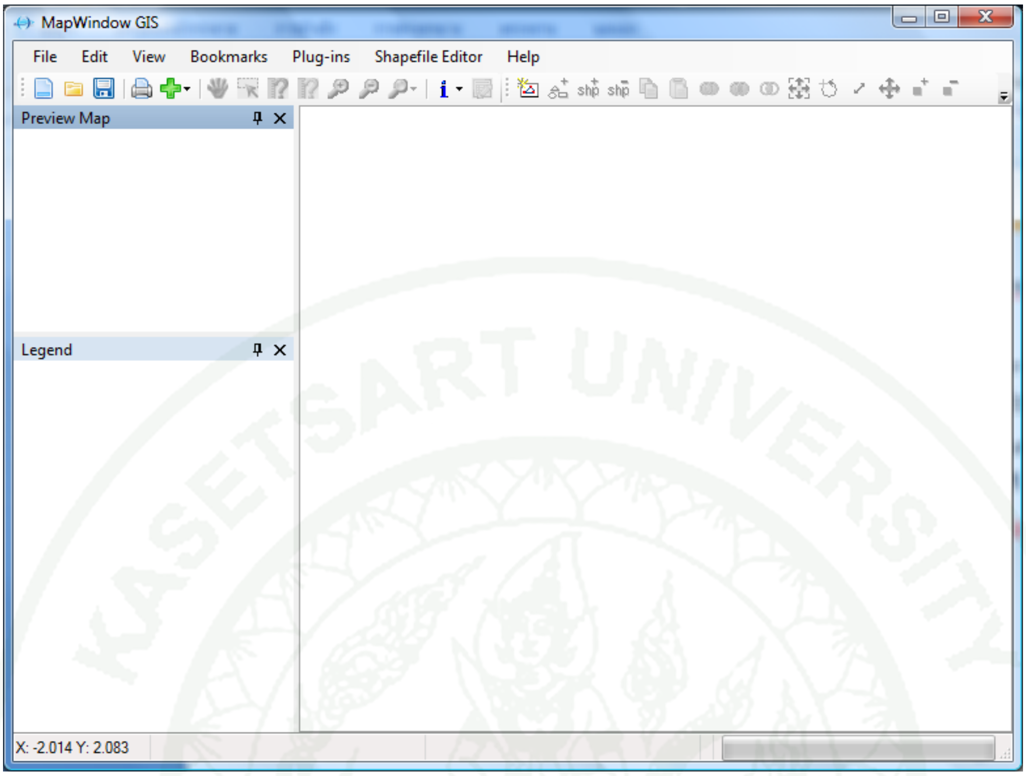


Figure 67 MapWindow GIS software

3. Plug-in Development

The Plug-in was developed using VB .NET and compiled as a DLL file for the MapWindow desktop. The plug-in has three main components:

- Water application uniformity calculations
- Pipe design and hydraulic calculations
- Irrigation sprinkler system layout design

A. Irrigation Sprinkler Water Application Uniformity

Irrigation Sprinkler Water Application Uniformity is the final part of the Irrigation Sprinkler Layout Design Plug-in (Figure68). It used for computing the water application uniformity from each overlapping sprinkler in operation. In detail, a sprinkler in a planted area can have different types and operating pressures. For example, one type of sprinkler might be used in the interior of the field, while another type is used at the field boundaries. Operating pressure varies throughout a field due to elevation differences and pipe friction losses. The user can directly assign sprinkler properties such as sprinkler location (x, y), sprinkler nozzle type, and pressure to each sprinkler in a field. Or, the user can use the design data and some results (such as hydraulic pressure from the hydraulic model) from previously invoked model processes, including hydraulic calculations and layout design. This process requires two inputs: (1) a sprinkler shapefile; and, (2) a planted-area shapefile. The user can use the editing tool of plug-in to add a new sprinkler, delete one or more sprinklers, change a sprinkler position, assign a sprinkler nozzle type, change the sprinkler operating angle (e.g. full circle or partial circle), and specify the operating pressure. The step-by-step process for using this part of the plug-in is described below.

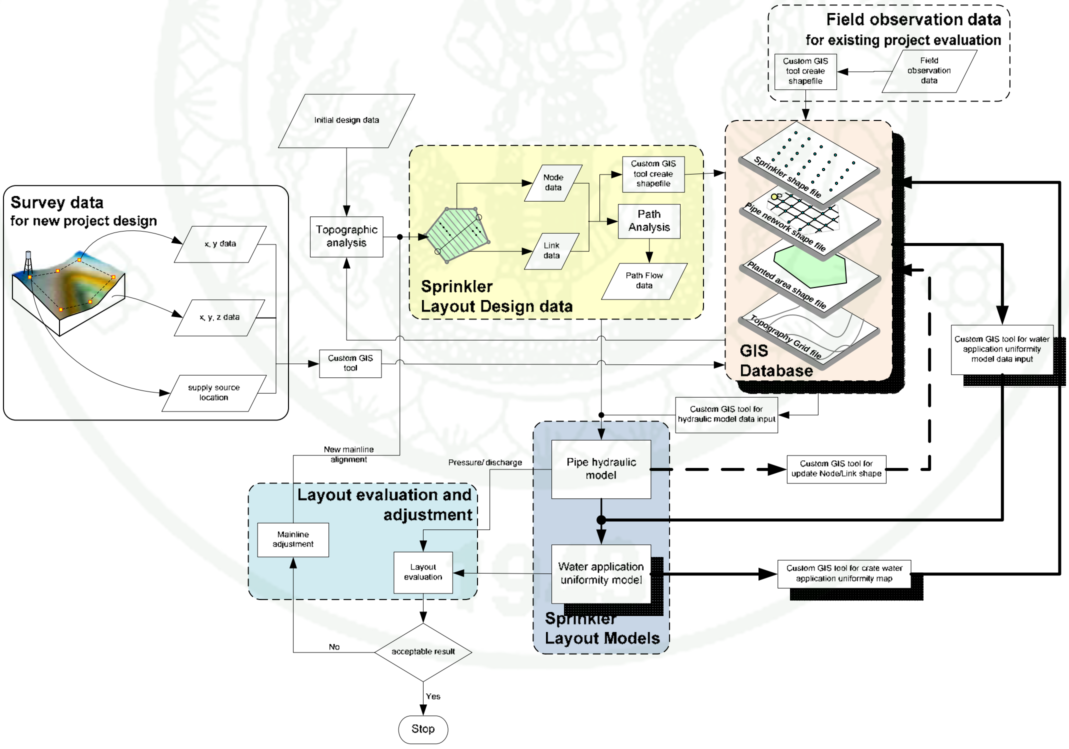


Figure 68 Water application uniformity diagram

STEP 1: Open project data

MapWindow project data are stored in a file which includes a list of shapefiles, grid files, and or image files. The data file opening process for a MapWindow project includes two steps: (1) clicking on the open-project button ①; and (2) MapWindow will show the open-file dialog ② for selecting a MapWindow project data file as shown in Figure69.

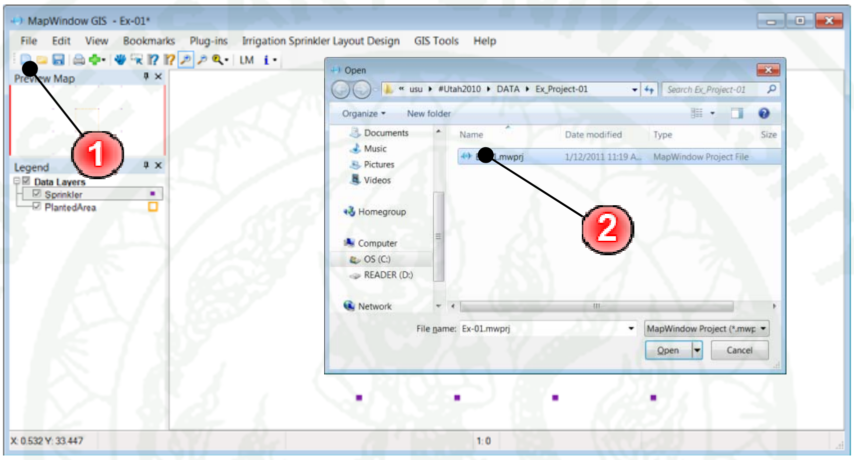


Figure 69 Open project data

After MapWindow opens the project data (in this example it is Ex-01.mwprj”) it displays all the GIS layers as shown in Figure70.

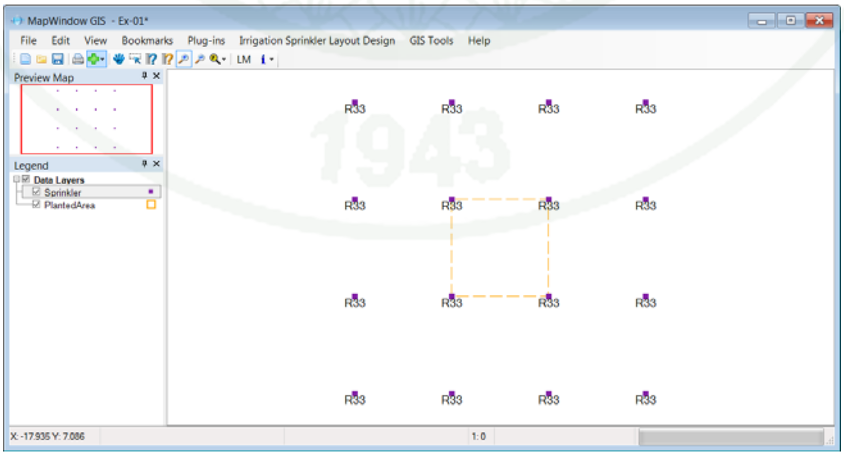
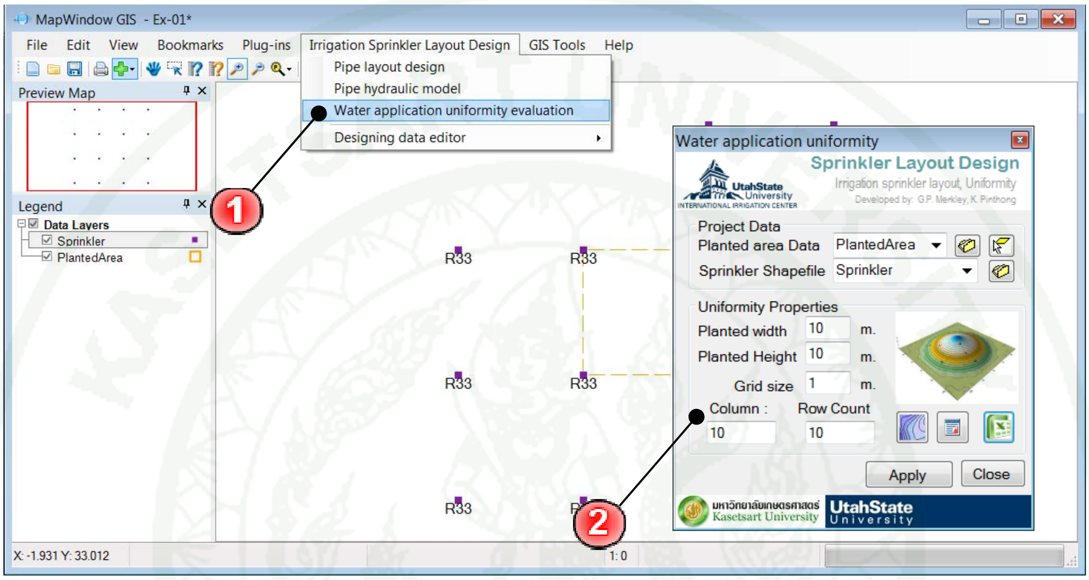


Figure 70 The GIS layer for irrigation water application uniformity

STEP 2: Open irrigation sprinkler layout editor plug-in

To use the Irrigation Sprinkler Layout Editor plug-in, the user can click on the plug-in water application evaluation menu, and the plug-in will display the Water application uniformity dialog as shown in Figure71.



Project Data
Planted area Data: PlantedArea
Sprinkler Shapefile: Sprinkler

Uniformity Properties
Planted width: 10 m.
Planted Height: 10 m.
Grid size: 1 m.
Column : 10
Row Count: 10

Figure 71 Water application uniformity dialog

STEP 3: Assign a sprinkler nozzle and properties

To permit the user to edit the sprinkler data, the USUKU model was developed as a group of sprinkler editing tools, such as the tool for inserting a sprinkler, a tool for deleting an existing sprinkler, a sprinkler properties editing tool, a sprinkler moving tool to change a sprinkler location, and a tool to specify the sprinkler rotation angle (360° or less). To edit the sprinkler data, click Designing data editor >> sprinkler ① (see Figure71). The program will show the sprinkler data editing dialog ②as shown in Figure72.

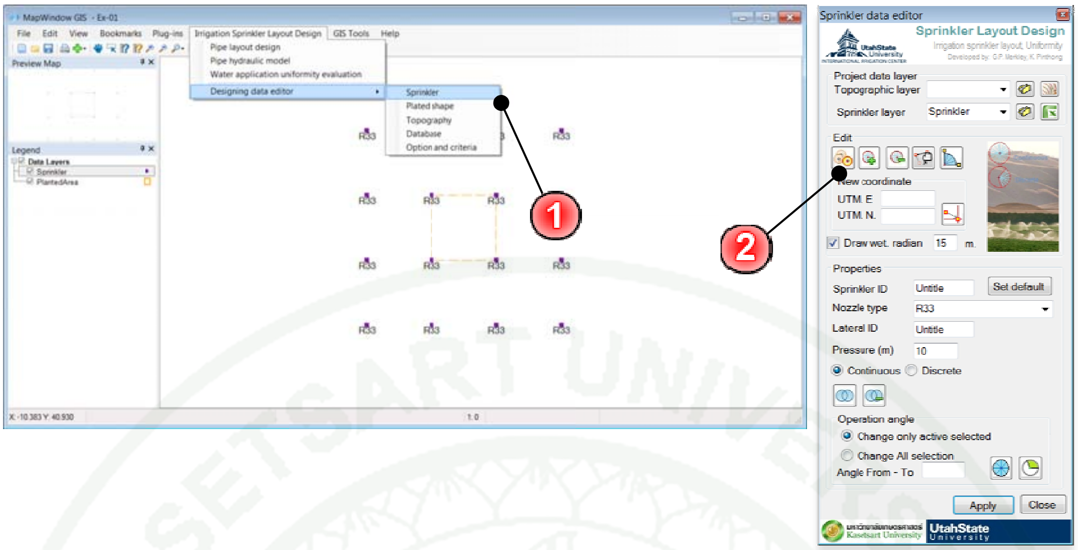


Figure72 Sprinkler properties

STEP4: Add, Remove, Edit the Sprinkler Operating Angle

- Add a sprinkler

The user can add a sprinkler by clicking on the add button ① and then clicking on the desired location on the map ②. After clicking on the map the custom GIS tool included in USUKU will insert a new sprinkler as shown in Figure73.

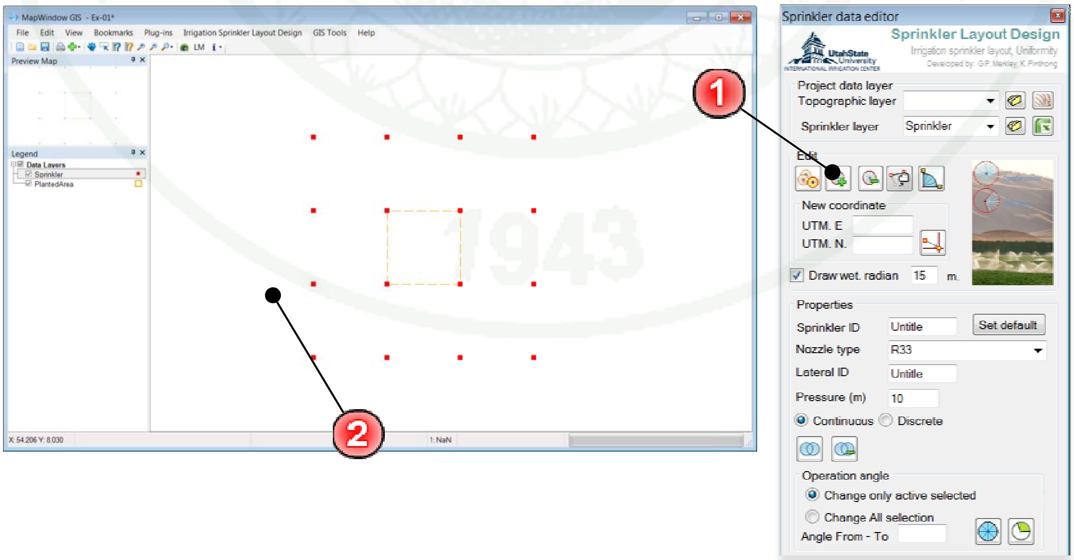


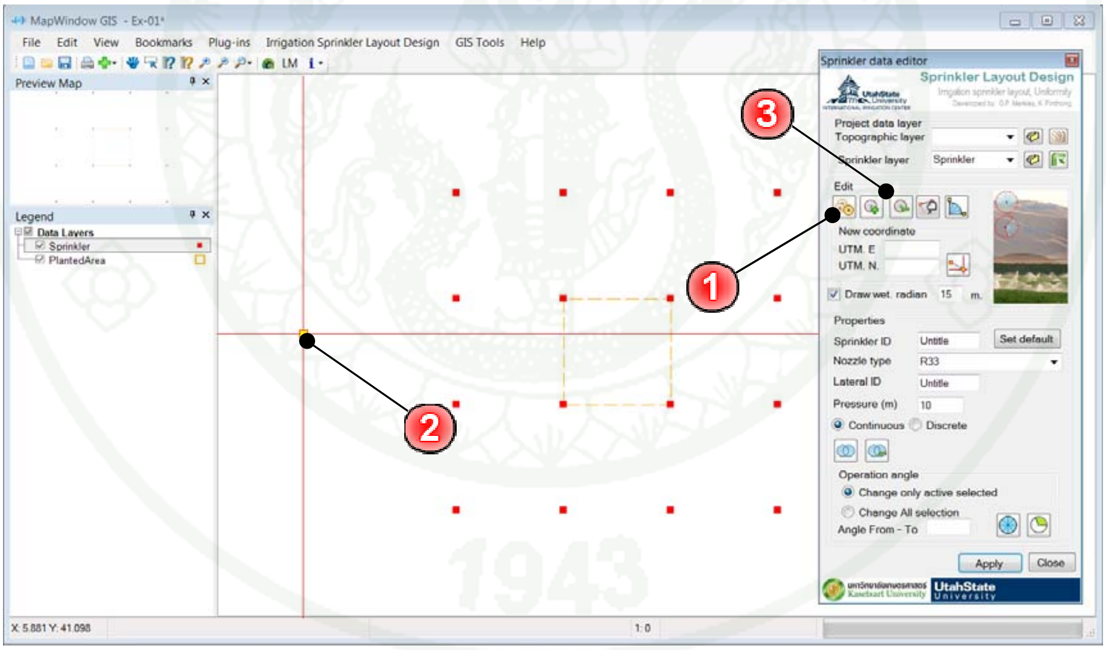
Figure 73 Process for adding a new sprinkler

- Remove a sprinkler

To remove a sprinkler, the user must select an existing sprinkler by using the selection tool ①, and then select by dragging a rectangular area which includes the sprinkler to be removed ②, then clicking on the sprinkler delete button③. The process for sprinkler deletion is shown in Figure74.

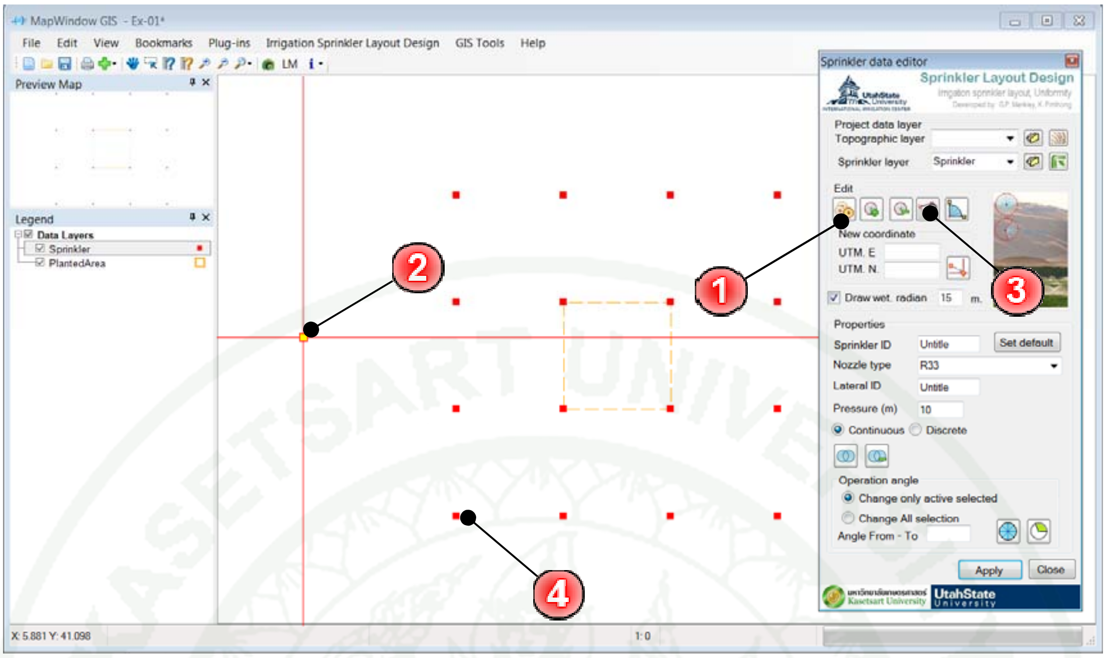
- Move sprinkler location

To move a sprinkler location, the user must select the sprinkler to be moved by using the selection tool ①. USUKU has two methods for moving a sprinkler location: (1) assign a new location using the mouse; and, (2) assign the location by entering specific coordinates. The processes for sprinkler movement are shown in Figures75 and 76.



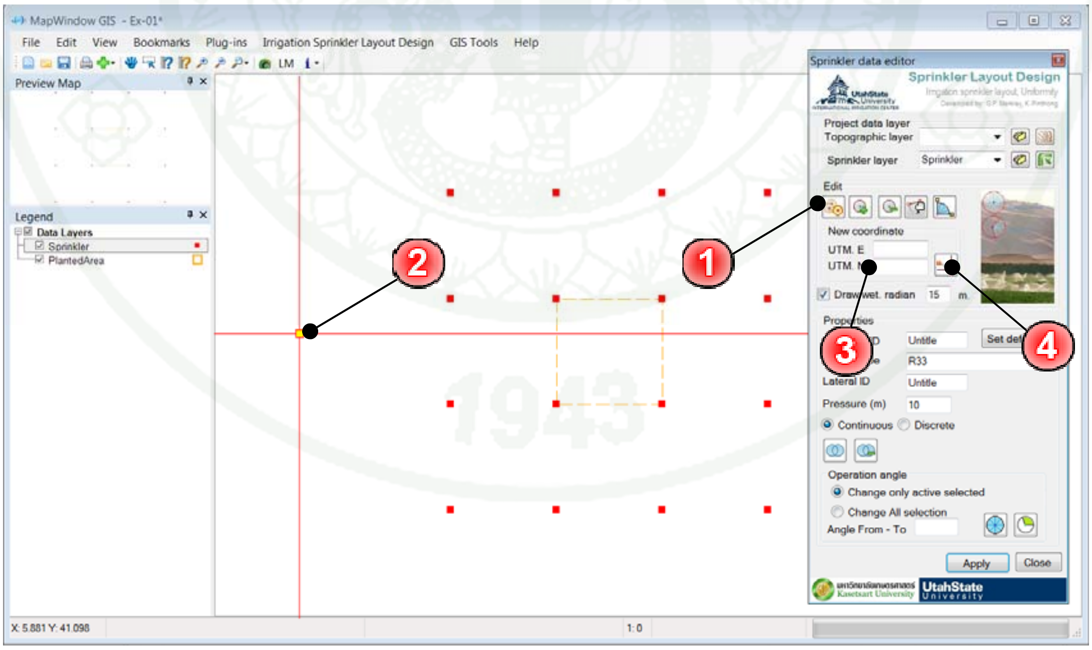
Topographic layer:
Sprinkler layer: Sprinkler
UTM. E:
UTM. N.:
☑ Draw wet. radian 15 m.
Sprinkler ID: Untitle
Nozzle type: R33
Lateral ID: Untitle
Pressure (m): 10
● Continuous ○ Discrete
● Change only active selected
○ Change All selection
Angle From - To:

Figure 74 Remove sprinkler process.



Project data layer
Topographic layer
Sprinkler layer: Sprinkler
Edit
New coordinate
UTM. E
UTM. N
☑ Draw wet. radian 15 m.
Properties
Sprinkler ID: Untitle
Nozzle type: R33
Lateral ID: Untitle
Pressure (m): 10
● Continuous ○ Discrete
Operation angle
● Change only active selected
○ Change All selection
Angle From - To
X: 5.881 Y: 41.098
1:0

Figure75 Move sprinkler location process (assign the new location by a mouse click on the map).

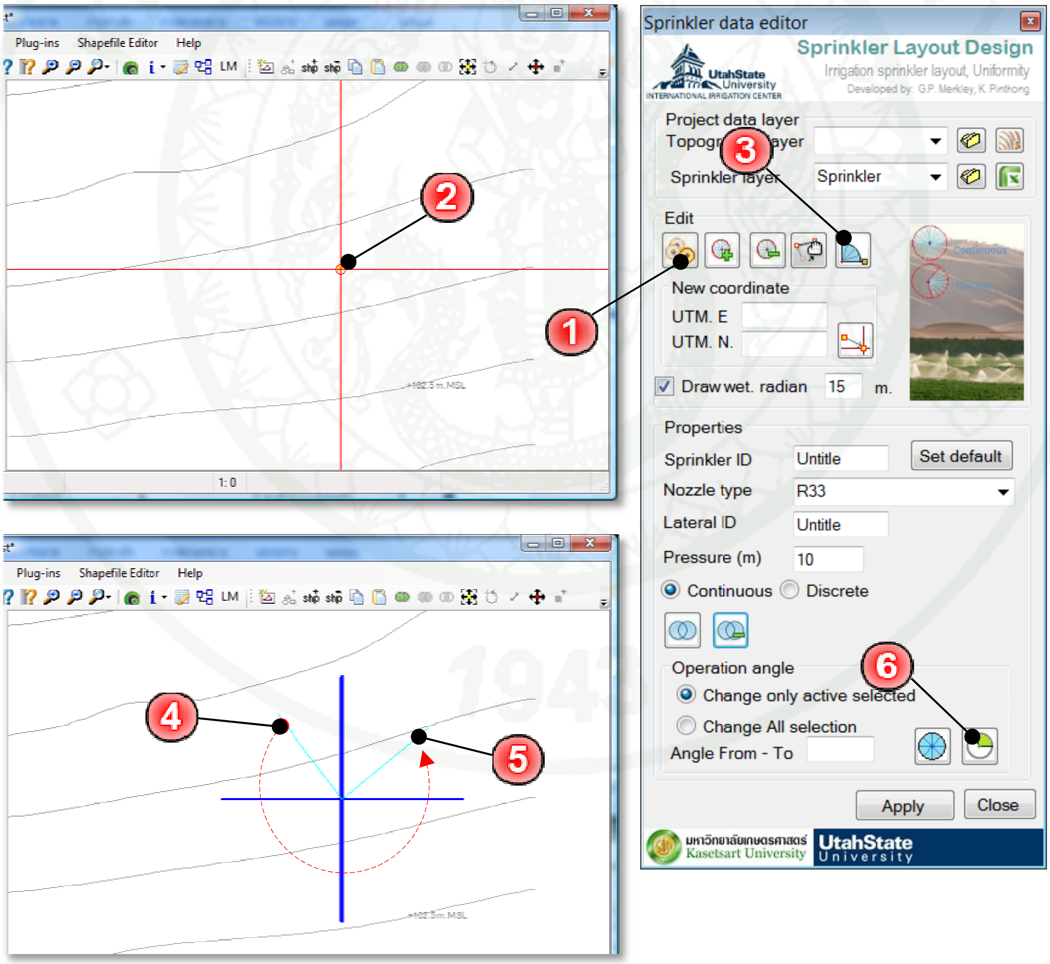


Project data layer
Topographic layer
Sprinkler layer: Sprinkler
Edit
New coordinate
UTM. E
UTM. N
☑ Draw wet. radian 15 m.
Properties
Sprinkler ID: Untitle
Nozzle type: R33
Lateral ID: Untitle
Pressure (m): 10
● Continuous ○ Discrete
Operation angle
● Change only active selected
○ Change All selection
Angle From - To
X: 5.881 Y: 41.098
1:0

Figure 76 Move sprinkler location process (assign the new location by specifying the coordinates).

- Edit sprinkler operating angle

Normally, sprinklers operate continuously in a full circle, and this is the default in USUKU, but some sprinklers cannotoperate in this way, such as asprinkler located on a field edge or in a field corner. The user can define the angle by selecting the sprinkler using the selection tool ①, selecting a sprinkler on the map ②, then clicking on the wetted area assignment button ③. A blue cross will be shown on the map at the selected sprinkler location. Then the user clicks on the map to specify the starting angle ④ and closing angle ⑤, and clicks on the button ⑥. The wetted area of the sprinkler is then determined by a counter-clockwise angle (from opening to closing angle), as shown in Figures77and78.



Project data layer
Topography layer
Sprinkler layer: Sprinkler
UTM. E
UTM. N.
☑ Draw wet. radian 15 m.
Sprinkler ID: Untitle
Nozzle type: R33
Lateral ID: Untitle
Pressure (m): 10
● Continuous ○ Discrete
Operation angle
● Change only active selected
○ Change All selection
Angle From - To

Figure 77 The process for defining the operating angle of a sprinkler.

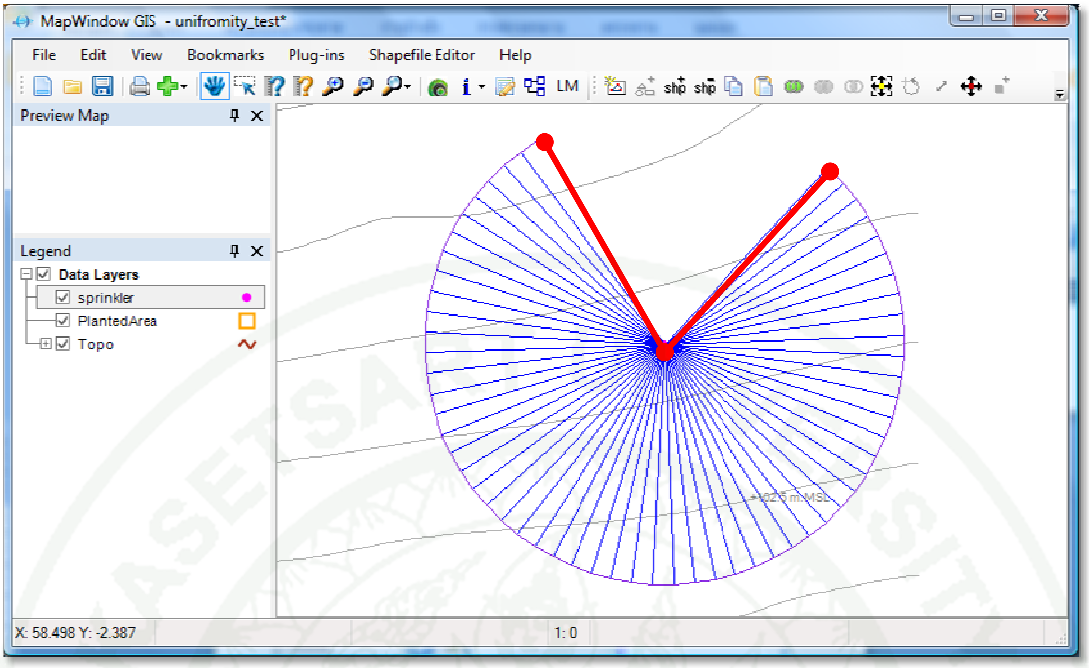
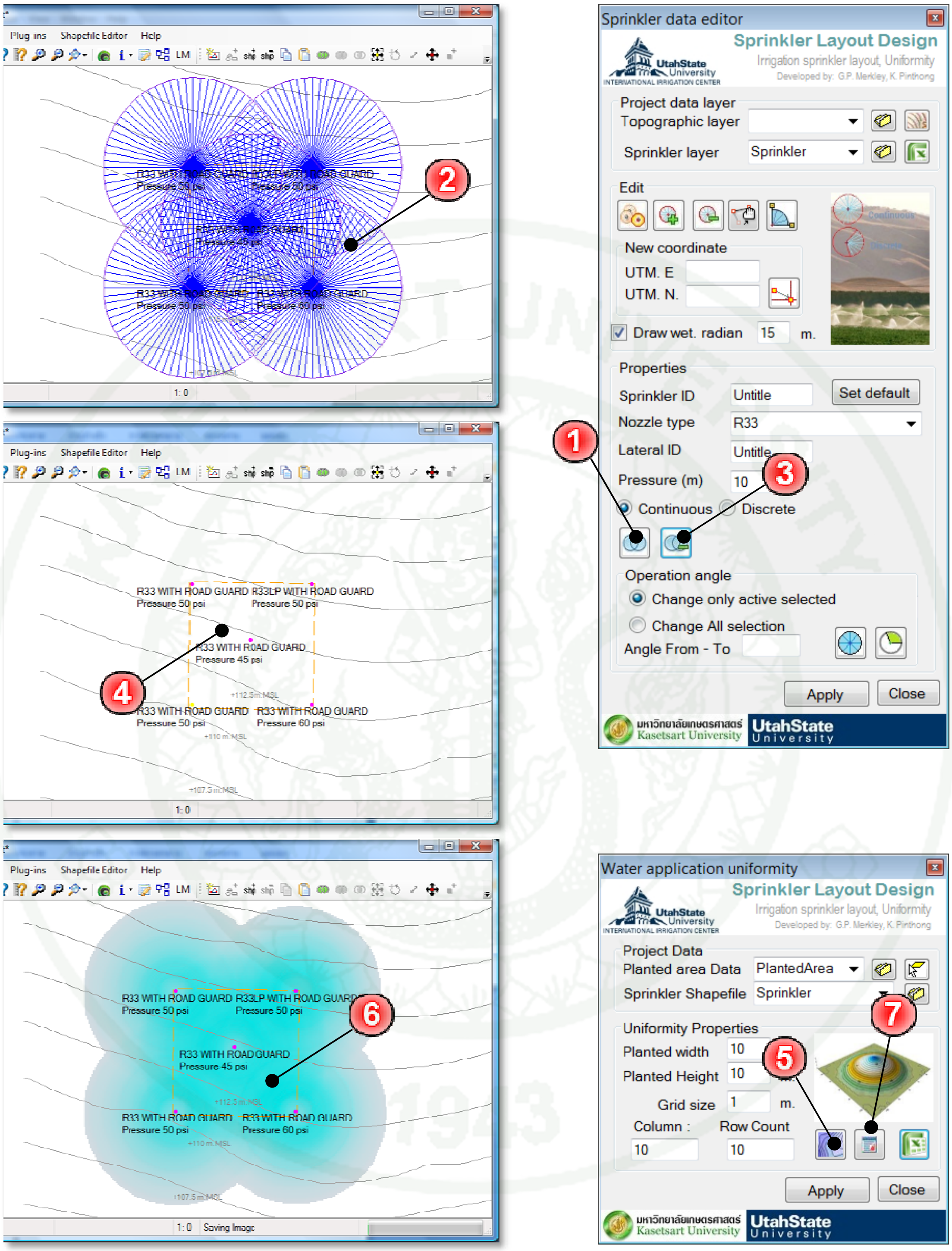


Figure 78 Wetted area of an operating sprinkler.

STEP5: Uniformity map

Before creating a water application uniformity map, the user can preview the wetted area of water application and water overlapping map by clicking on button ① shown in Figure79. USUKU will use data from the field AngF and AngT (Angle From and Angle To) to make a wetted-area map ② of each sprinkler in the sprinkler shape file. To clear the wetted area drawing, the user must click on button ③ and then the drawing area is cleared ④. To calculate the water application overlapping, click on button ⑤, then USUKU will take a few minutes to compute the water overlapping. The computation time depends on the number of simulated catch cans. After calculations are completed, USUKU will automatic create a water application map and show the uniformity coefficient report by clicking on button ⑦, as shown in Figures79 and 80.



Sprinkler data editor

Sprinkler Layout Design
Irrigation sprinkler layout, Uniformity
Developed by: G.P. Merkley, K. Pinthong

Project data layer
Topographic layer
Sprinkler layer: Sprinkler

Edit

New coordinate
UTM. E
UTM. N.
☑ Draw wet. radian 15 m.

Properties
Sprinkler ID: Untitle
Nozzle type: R33
Lateral ID: Untitle
Pressure (m): 10
● Continuous ○ Discrete

Operation angle
● Change only active selected
○ Change All selection
Angle From - To

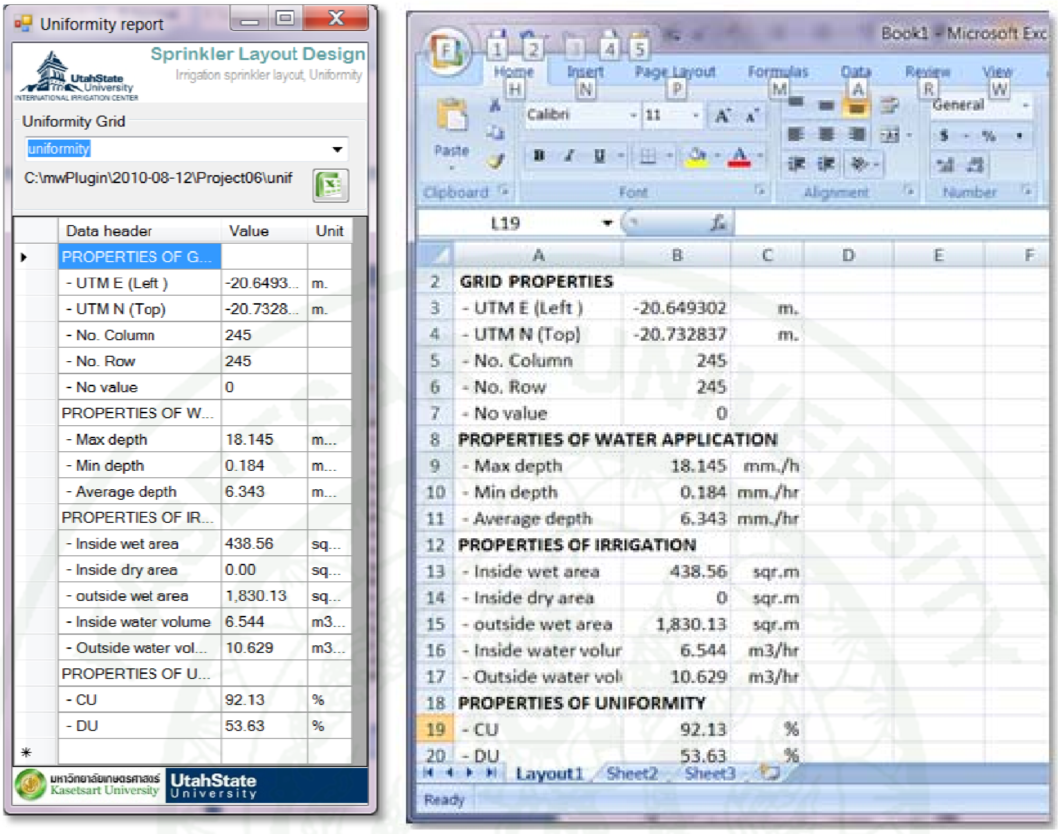
Water application uniformity

Sprinkler Layout Design
Irrigation sprinkler layout, Uniformity
Developed by: G.P. Merkley, K. Pinthong

Project Data
Planted area Data: PlantedArea
Sprinkler Shapefile: Sprinkler

Uniformity Properties
Planted width: 10
Planted Height: 10
Grid size: 1 m.
Column: 10
Row Count: 10

Figure 79 Water application map



Uniformity Grid: uniformity

C:\mwPlugin\2010-08-12\Project06\unif

Data header	Value	Unit
PROPERTIES OF G...		
- UTM E (Left)	-20.6493...	m.
- UTM N (Top)	-20.7328...	m.
- No. Column	245	
- No. Row	245	
- No value	0	
PROPERTIES OF W...		
- Max depth	18.145	m...
- Min depth	0.184	m...
- Average depth	6.343	m...
PROPERTIES OF IR...		
- Inside wet area	438.56	sq...
- Inside dry area	0.00	sq...
- outside wet area	1,830.13	sq...
- Inside water volume	6.544	m3...
- Outside water vol...	10.629	m3...
PROPERTIES OF U...		
- CU	92.13	%
- DU	53.63	%

L19

	A	B	C
2	GRID PROPERTIES		
3	- UTM E (Left)	-20.649302	m.
4	- UTM N (Top)	-20.732837	m.
5	- No. Column	245	
6	- No. Row	245	
7	- No value	0	
8	PROPERTIES OF WATER APPLICATION		
9	- Max depth	18.145	mm./h
10	- Min depth	0.184	mm./hr
11	- Average depth	6.343	mm./hr
12	PROPERTIES OF IRRIGATION		
13	- Inside wet area	438.56	sqr.m
14	- Inside dry area	0	sqr.m
15	- outside wet area	1,830.13	sqr.m
16	- Inside water volur	6.544	m3/hr
17	- Outside water vol	10.629	m3/hr
18	PROPERTIES OF UNIFORMITY		
19	- CU	92.13	%
20	- DU	53.63	%

Figure 80 Water application evaluation parameters

B. Pipe Hydraulic Model

The pipe hydraulic model for USUKU (Figure81) is a gravity-fed model for a branching pipe network. The input data for the hydraulic model consist of node data and link data. All data are in the form of shape files (points and lines) and the shape attributes. The user must provide the location of the water supply (a point), and then USUKU will use both data (node and link) to compute the flow path (from the water supply to all sprinkler locations) to all nodes in the project area. The hydraulic model uses nodes, links, and path data to compute pipe hydraulic properties, including pressure, average flow velocity, and discharge.

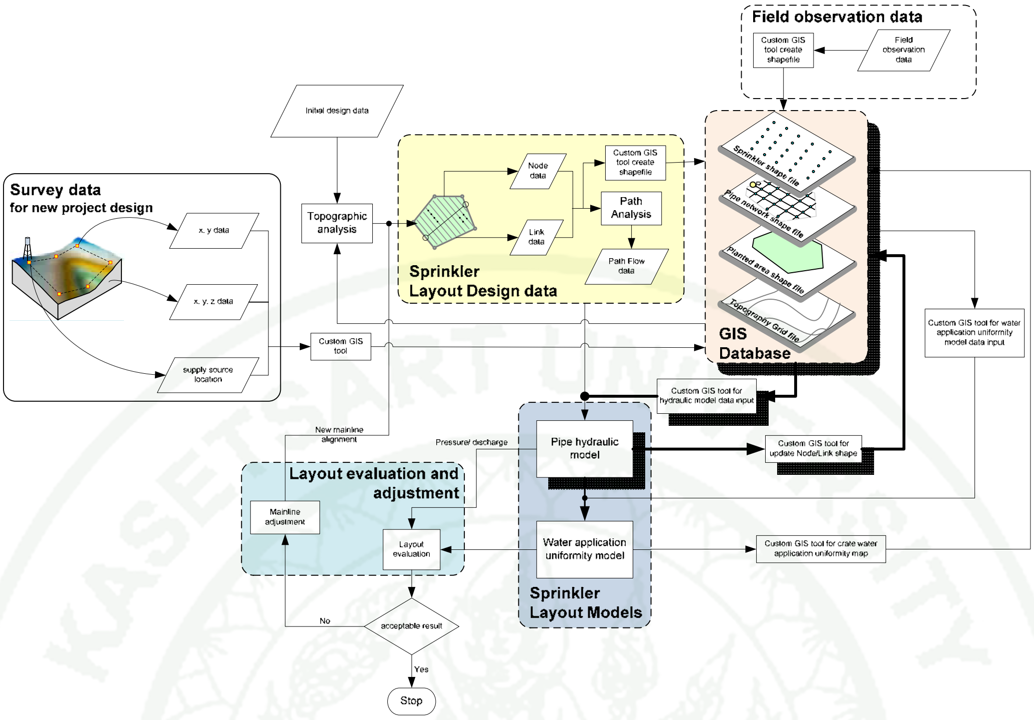


Figure 81 Hydraulic model components in USUKU

To begin the pipe hydraulic computation process, the user clicks on the pipe hydraulic model menu item in the main plug-in menu bar ①. Figure 82 shows the gravity-fed hydraulic model dialog window ② and the pipe simulation data, including sprinkler shape file data ③, pipe shape file data ④, topographic data ⑤, tank height ⑥, tank elevation ⑦, and simulation options ⑧.

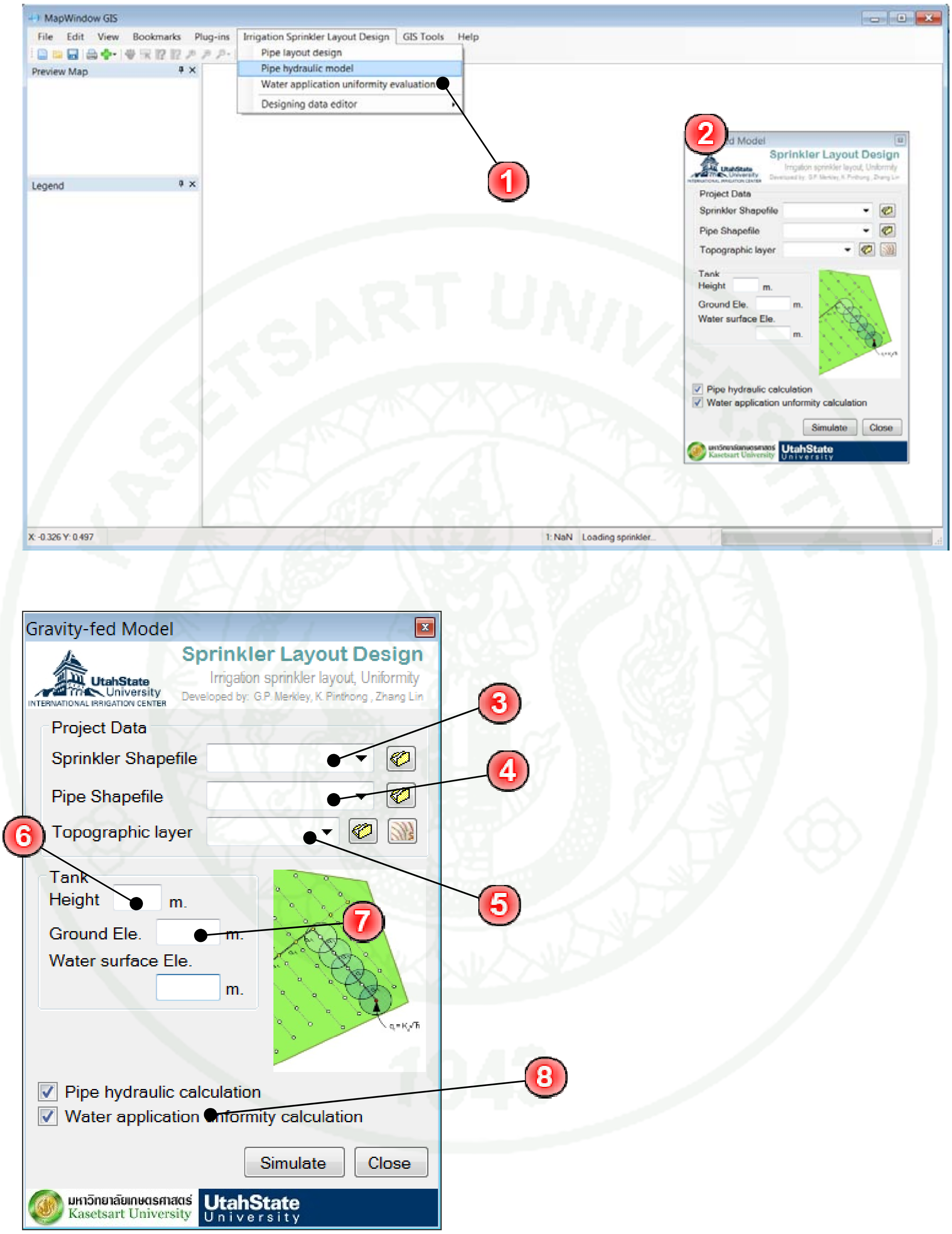


Figure 82 Gravity-fed model dialog and features

1. Pipe hydraulic calculations

The user can select all project data for the list of layers in the MapWindow legend, or can open them directly from the shape data file. When opening a new layer, USUKU will automatically add the new layer to the MapWindow legend. Tank data (at the water supply location) include the tank height above the supply source location. The ground elevation is the supply source elevation. These data are obtained automatically from the topographic data layer. Water surface elevation is the elevation of water surface in the tank, and it can equal the tank height plus the ground elevation at the water supply location.

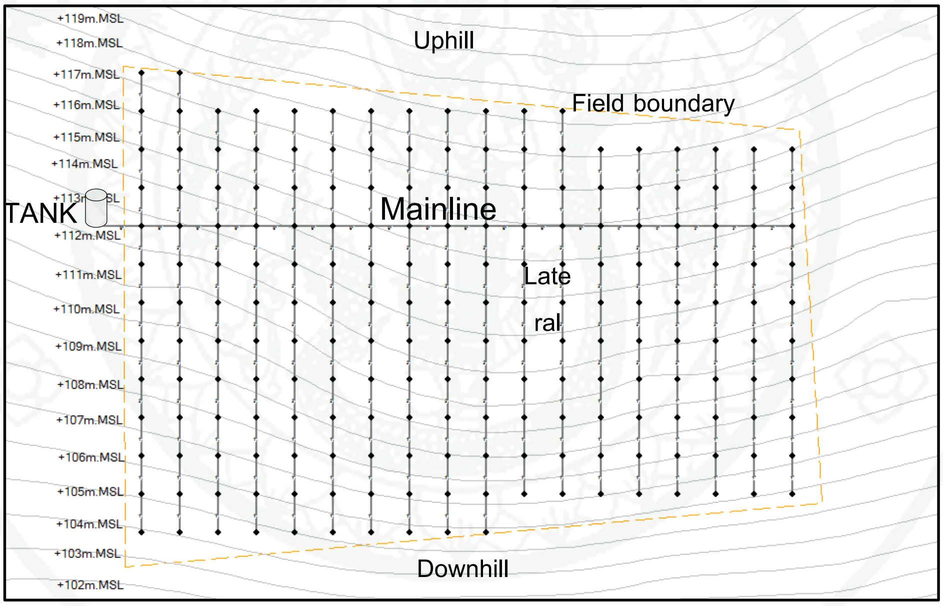
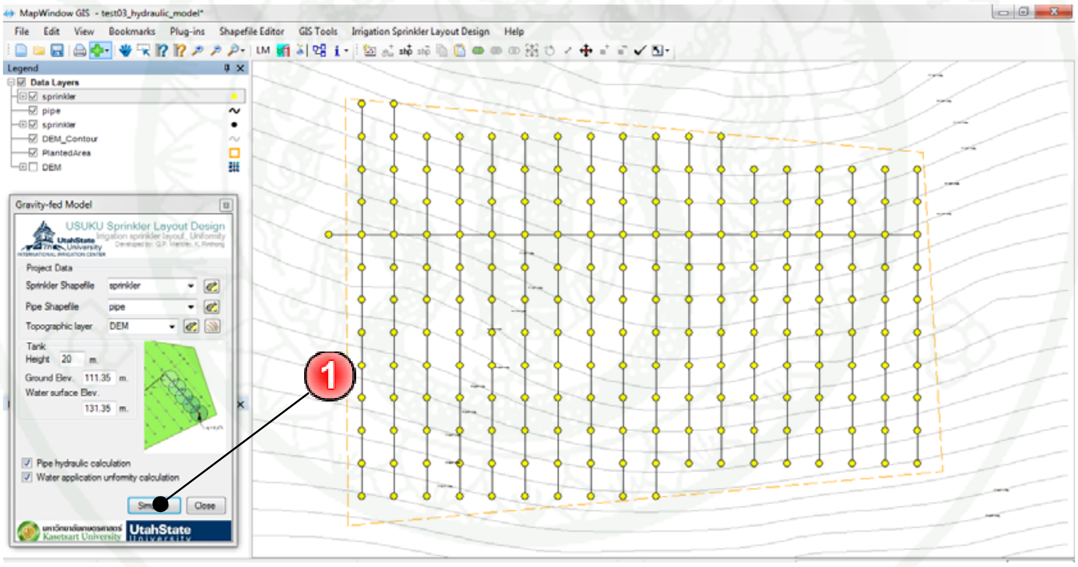


Figure 83 Plan view of the field hydraulic simulation test

The test field was trapezoidalshape with approximately dimensions of 115m. x180 m., for a total area of 20,500 m^2. The water sourcewas given a fixed pressure head in each simulation, and allcalculated sprinkler flow rates and pressures were based onthis specified value, field topography, pipe diameters andlengths, and sprinkler P versus q relationships. Figure 83 shows topography and the location of thefield area. As seen in Figure83, the mainline is located at30% of length from uphill side of the field, with a length about30-40 m, and the watersource (constant 20 m.) at one side of mainline location.The pipe system layout is including 18 later and 205 Nelson R33 sprinkler with spacing (S_l, S_e) 10 x 10 m^2.

To simulation the user can select from the following computational processes: (1) calculate pipe hydraulics only; or, calculate pipe hydraulics and compute water application uniformity after finishing the hydraulic computational process. After defining all hydraulic computation data and options, the user can click on the simulation button ① (Figure84), upon which the gravity-fed model will process for a few minutes to generate hydraulic results. The calculation time depends on the number of node links and junctions in the system layout.


MapWindow GIS - test03_hydraulic_model*

Gravity-fed Model

Project Data

Sprinkler Shapefile: sprinkler

Pipe Shapefile: pipe

Topographic layer: DEM

Tank

Height: 20 m.

Ground Elev.: 111.35 m.

Water surface Elev.: 131.35 m.

☑ Pipe hydraulic calculation

☑ Water application uniformity calculation

Figure 84 Pipe hydraulic model simulation window

After a simulation finishes, the model can report hydraulic property results in terms of nodes and links. The results can be produced as a table and a map in the GIS as shown in Tables 5 and 6, and in Figure85. The results are considered to be acceptable according to the difference between the maximum and minimum pressures in the planted area, which should not be greater than 20% of the average sprinkler pressure.

Table 5 Sample of hydraulic property results for each node in the pipe network

Node	X (m)	Y (m)	Z (m)	H (m)	Q (cms)	k_d	Type	H_f (m)
1	460.55	375.39	114.38	20	0.0003	7.58E-05	Tank	0
2	493.65	480.3	113.87	17.22	0.0003	7.58E-05	Junction	0.2809
3	473.65	480.3	113.81	15.91	0.0003	7.58E-05	R33	1.3699
4	453.65	480.3	113.72	15.62	0.0003	7.58E-05	R33	0.3763
5	513.65	480.3	113.90	5.78	0.0002	7.58E-05	R33	1.6557
6	533.65	480.3	113.92	4.84	0.0002	7.58E-05	R33	0.9169
7	553.65	480.3	113.90	4.44	0.0002	7.58E-05	R33	0.4199
8	573.65	480.3	113.87	4.35	0.0002	7.58E-05	R33	0.1153
9	493.65	460.3	113.37	18	0.0003	7.58E-05	Junction	1.0256
10	473.65	460.3	113.31	6.92	0.0002	7.58E-05	R33	1.2884
11	453.65	460.3	113.23	6.41	0.0002	7.58E-05	R33	0.5928
12	433.65	460.3	113.12	6.35	0.0002	7.58E-05	R33	0.1636
13	513.65	460.3	113.39	6.32	0.0002	7.58E-05	R33	1.8064
..	..	..	..	..	..	..	..	..
..	..	..	..	..	..	..	..	..
132	533.65	260.3	107.19	24.45	0.0004	7.58E-05	R33	0.1413
133	553.65	260.3	107.11	22.64	0.0004	7.58E-05	R33	1.8983

Table 6 Sample results for hydraulic properties according to pipe links

Link id	From Node	To Node	L (m)	Discharge (cms)	Diameter (in)	J (m/100 m)
1	1	46	13.99	0.0405	8"	0.665061
2	2	3	20	0.0006	1"	6.808306
3	3	4	20	0.0003	1"	1.885956
4	2	5	20	0.0007	1"	9.057838
5	5	6	20	0.0005	1"	4.857306
6	6	7	20	0.0003	1"	1.885956
7	7	8	20	0.0002	1"	0.890042
8	9	2	20	0.0016	2"	1.431915
9	9	10	20	0.0006	1"	6.808306
..	..	..	..	..	..	..
..	..	..	..	..	..	..
135	57	47	20	0.0023	2"	2.804186
136	71	57	20	0.0034	2"	5.783435

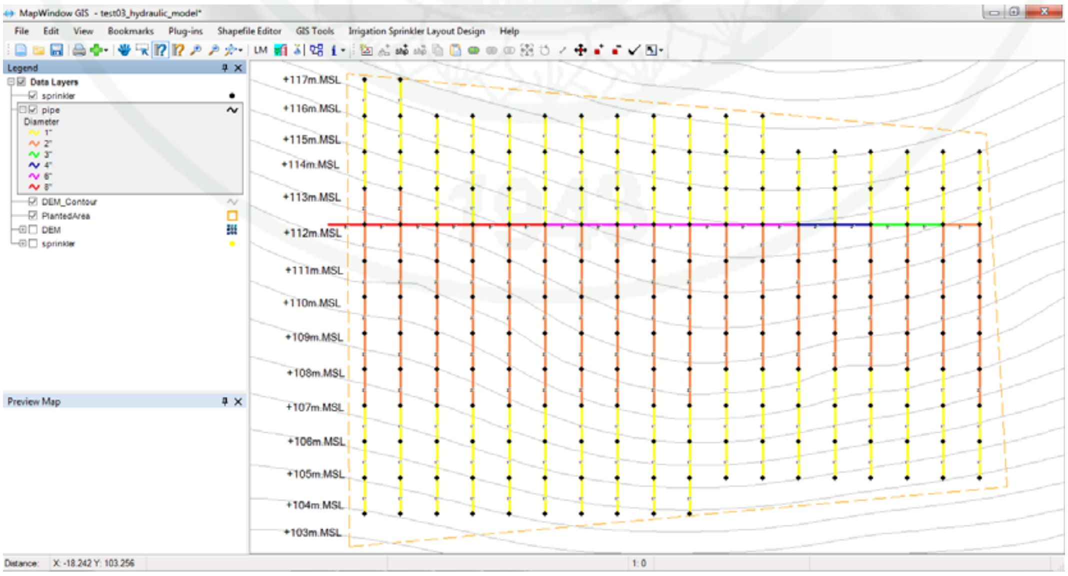


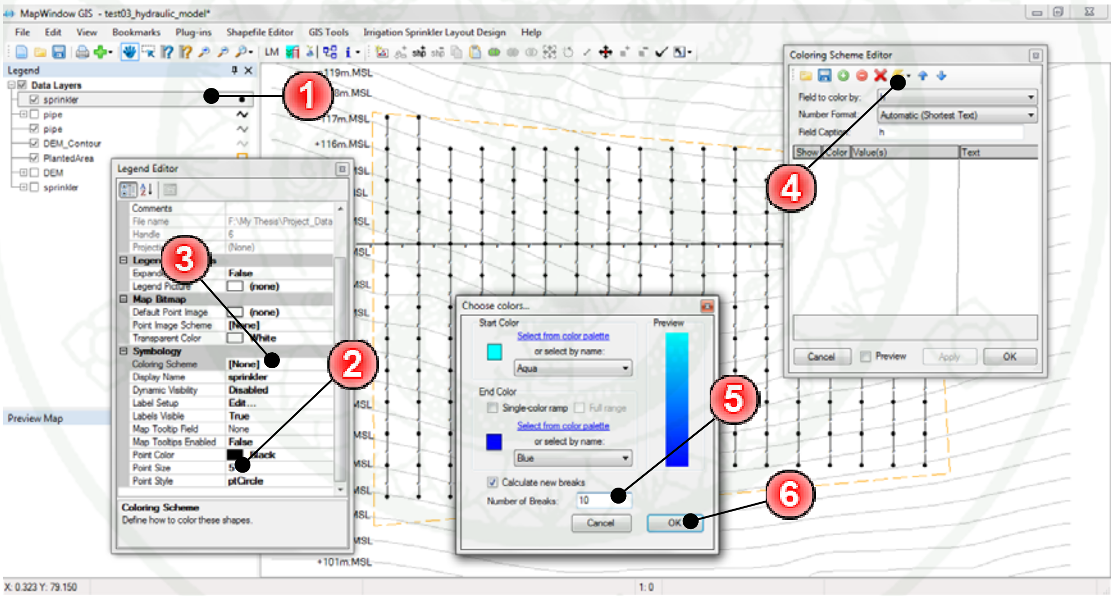
Figure 85 Pipes size result

2. Pressure map

STEP 1: Double click on layer “Sprinkler” at the map legend ①. MapWindow will pop-up a legend editing dialog.

STEP 2: Chang point size data ② (e.g. 50 pixels). MapWindow will display point that are 50 pixels on map.

STEP 3: Click on the “Coloring scheme” ③ at the legend editor. Then select field “H” (field pressure) and select option “Continuous ramp”④. MapWindow will show a dialog for the user to select the start color, the end color, and number of breaks ⑤, then click “OK”⑥. MapWindow will show color break and display values. Finally, click “OK”to confirm display of the pressure map as shown in Figures 86 and 87.



MapWindow GIS - test03_hydraulic_model*

Legend Editor

Comments
File name: F:\My Thesis\Project_Data
Handle: 6
Projection: (None)
Expanded: False
Legend Picture: (none)
Default Point Image: (none)
Point Image Scheme: [None]
Transparent Color: White
Coloring Scheme: [None]
Display Name: sprinkler
Dynamic Visibility: Disabled
Label Setup: Edit ...
Labels Visible: True
Map Tooltip Field: None
Map Tooltips Enabled: False
Point Color: Black
Point Size: 5
Point Style: ptCircle

Coloring Scheme
Define how to color these shapes.

Choose colors...
Start Color: Aqua
End Color: Blue
☐ Single-color ramp ☐ Full range
☑ Calculate new breaks
Number of Breaks: 10

Coloring Scheme Editor
Field to color by: h
Number Format: Automatic (Shortest Text)
Field Caption: h

Figure 86 Part one of the pressure map creation process

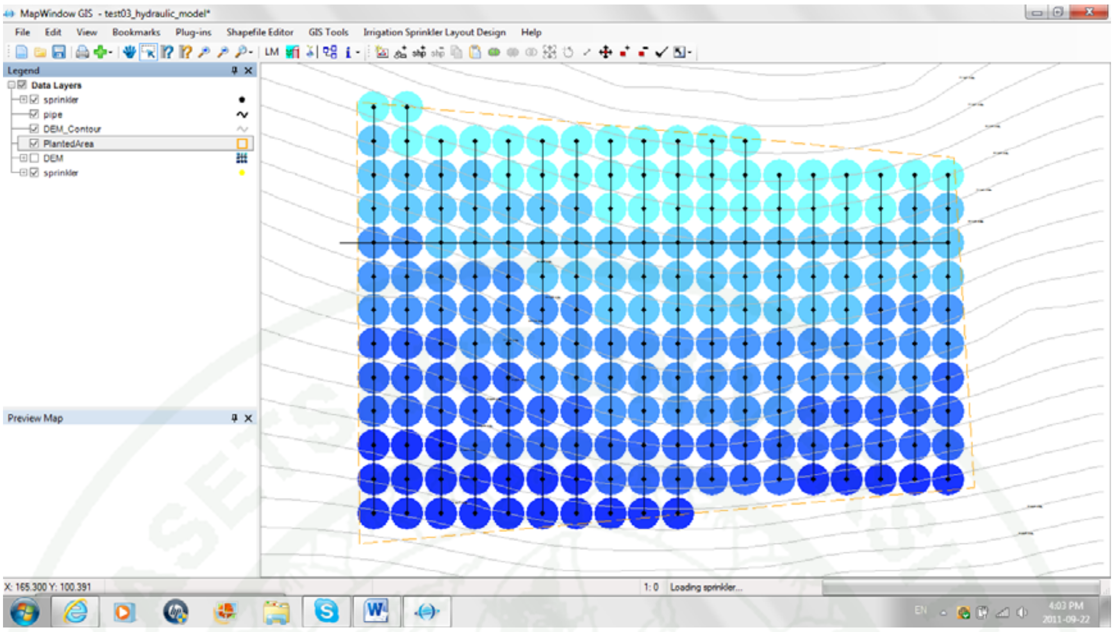


Figure 87 Part two of the pressure map creation process

C. Sprinkler layout design

The sprinkler layout design in USUKU needs two main data. These are topography data and the planted-area shape file and water supply location. However, USUKU prepares a custom GIS tool for converting field survey data to the GIS format used by USUKU. The methods for sprinkler layout design in USUKU can be separated by two methods, which are manual layout design and automatic layout design. The result of both methods (manual/automatic) is a shape file that consists of node and link, or sprinkler layer and pipe layer, as shown in the sprinkler layout design diagram in Figure 88.

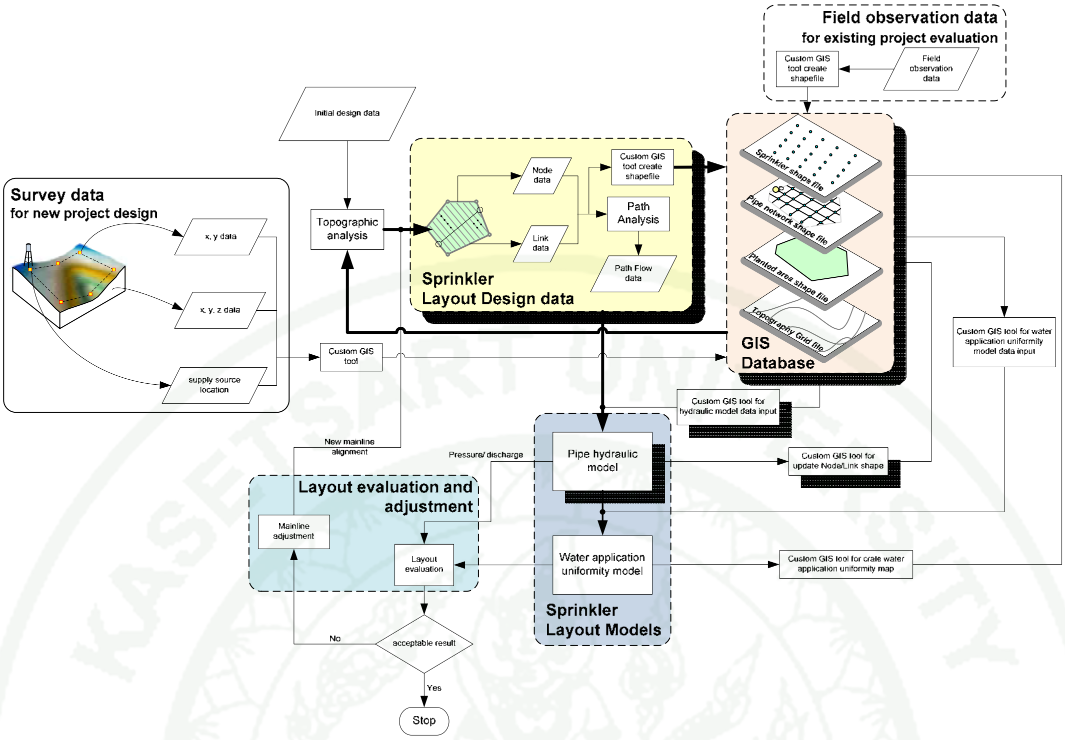


Figure 88 Sprinkler layout design diagram

1. Manually sprinkler layout design

For manual design, the user must provide two data sets, including a polygon shape file of the planted area, and an ESRI grid data file with site topography data. The planted area for manual design can be an irregular shape. To open the dialog for sprinkler layout design, the user can select the Irrigation Sprinkler Layout Design dialog from the main menu ①, then USUKU will show the design dialog ② as shown in Figure89. The details of the Irrigation Sprinkler Layout Design (Figure90) are: input data ① (topography and field shape), and design options (manual design ② or automatic design ③). The tools for manual design are: supply source location assignment, mainline alignment tool, sprinkler and pipe layout tool, sprinkler location and pipe system tool, clear-drawing tool, and create sprinkler layout system (node & link) as a shape file④. However, the mainline alignment data, sprinkler spacing, and water supply detail are shown as numeric values ⑤ for editing or assigning using the keyboard. Then, the mainline is positioned by drawing a line on the map using free line draw, horizontal line draw, or vertical draw options ⑥. It is possible to specify the computational process in three different ways ⑦:

- Design a sprinkler layout only
- Design a sprinkler layout and compute hydraulic propeties
- Design a sprinkler layout, compute hydraulic propeties, and compute water application overlapping and uniformity

To automatic layout design, USUKU uses a topography analysis process for creating a guide of mainline alignment. This guide for the mainline alignment process is the only process used in manual designs.

2. Manual Sprinkler layout design data

Next, the sprinkler design data (topographic/ field shape) and layout design dialog is opened. First, the water supply location is specified. The user can click on the map to specify the water supply location, or can use the assignment button ① and click on the map ② to assign the location. Alternatively, the user can input the water supply coordinates ③ and click the assign button ④ as shown in Figure91.

To manually align the mainline (Figure92), the user clicks on the button ① and clicks the first point on the map ②. Before clicking on the second point, the user can select a mainline alignment option (free line, vertical line, or horizontal line) ③, and then clicks on a second point on map④. On the other hand, the user can input the coordinates of two points and click the assign data button ⑤ to determine the mainline alignment.

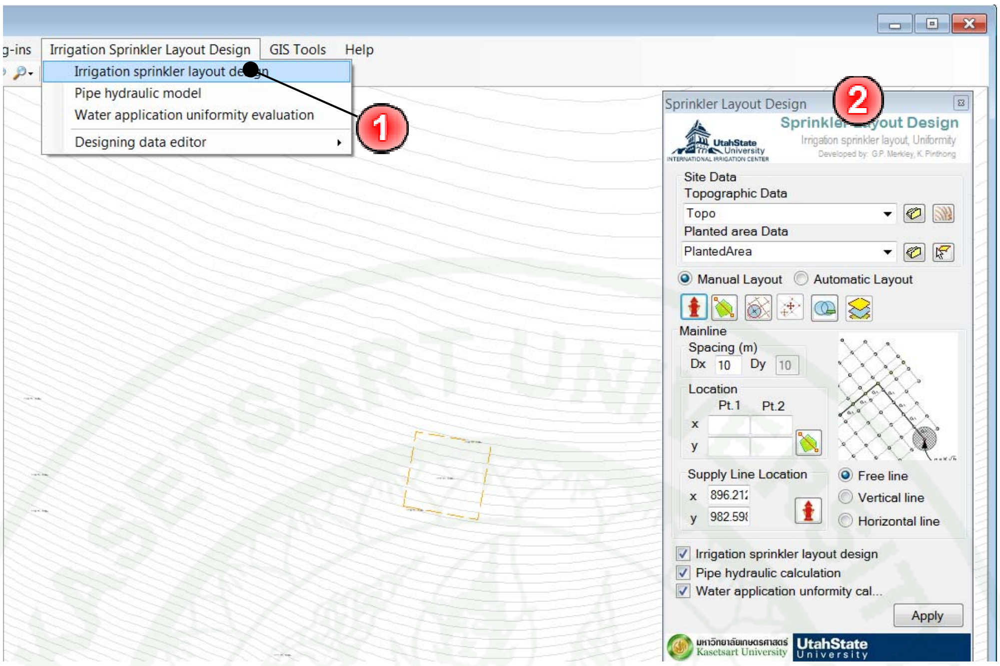


Figure 89 Irrigation sprinkler layout design dialog

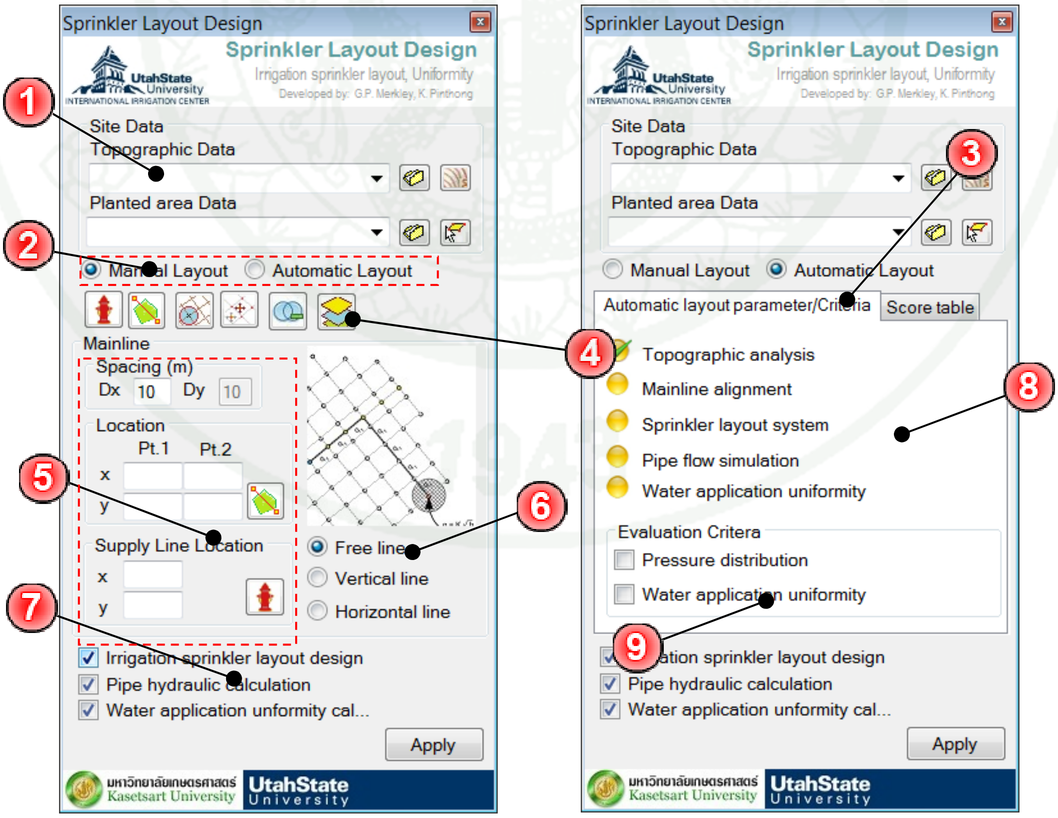
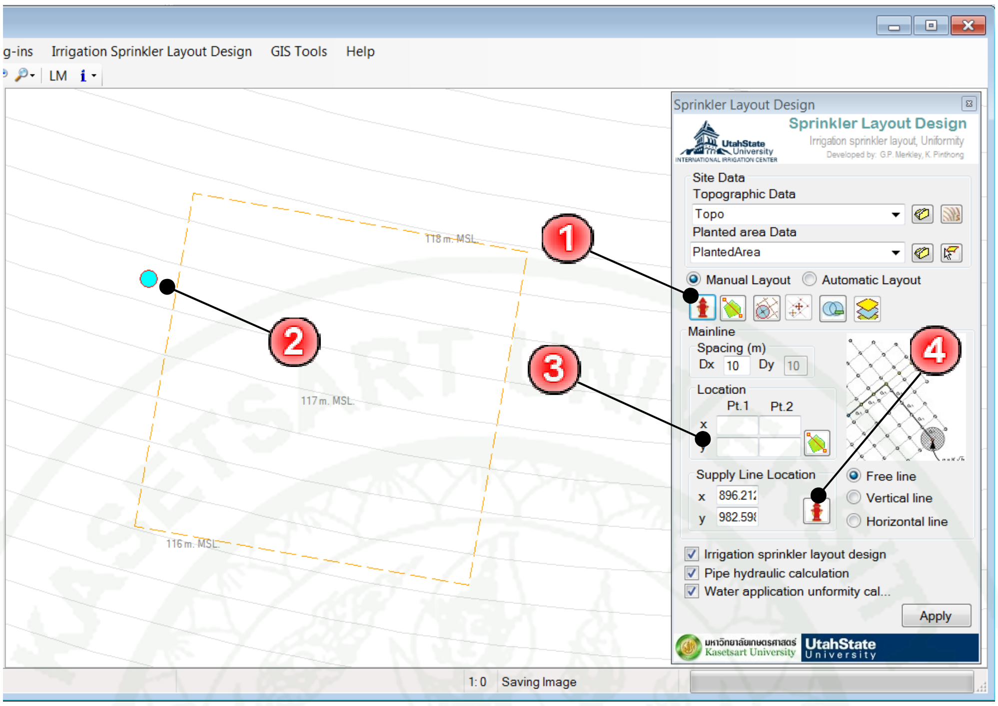
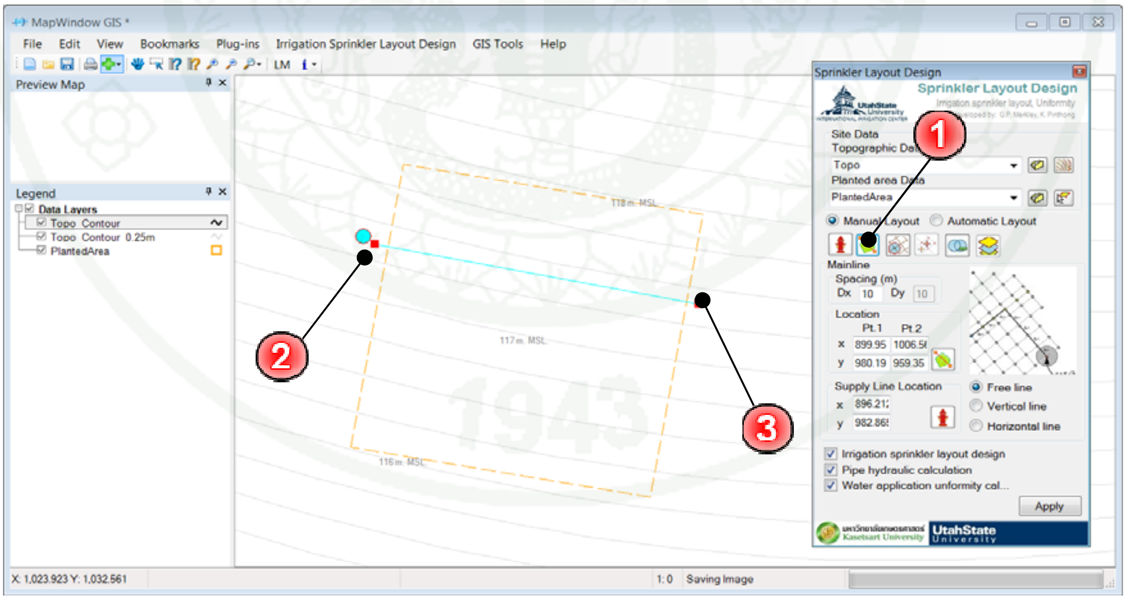


Figure 90 Detail of the irrigation sprinkler layout design dialog



Topographic Data: Topo
Planted area Data: PlantedArea
● Manual Layout ○ Automatic Layout
Spacing (m) Dx 10 Dy 10
Location Pt.1 Pt.2
Supply Line Location x 896.21 y 982.59
● Free line
○ Vertical line
○ Horizontal line
☑ Irrigation sprinkler layout design
☑ Pipe hydraulic calculation
☑ Water application unformity cal...
1:0 Saving Image

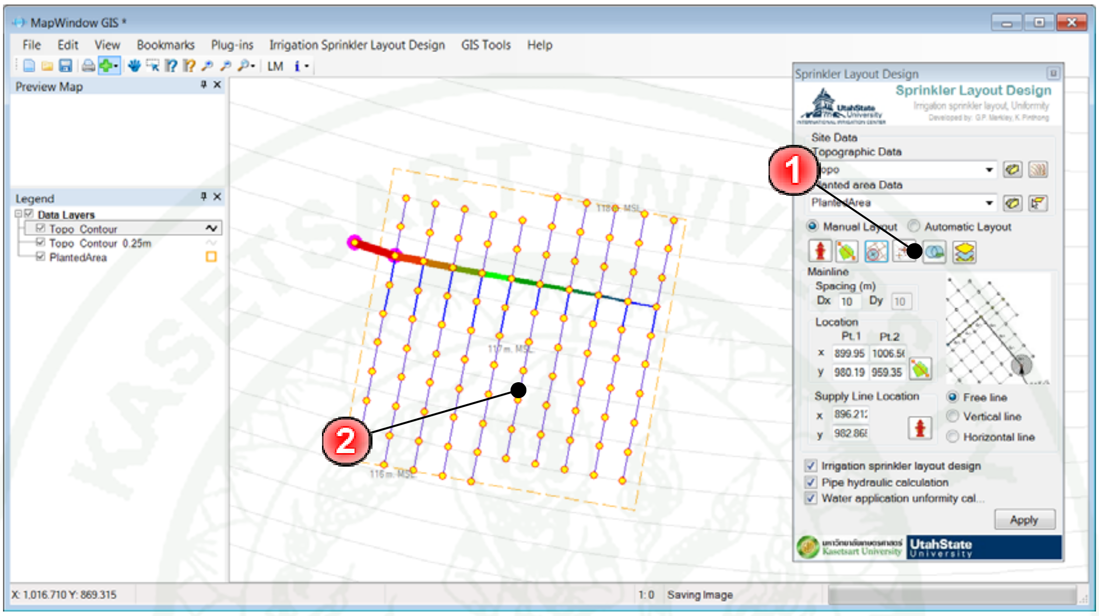
Figure 91 Supply source location assignment



Data Layers
☑ Topo_Contour
☑ Topo_Contour_0.25m
☑ PlantedArea
Topographic Data: Topo
Planted area Data: PlantedArea
● Manual Layout ○ Automatic Layout
Spacing (m) Dx 10 Dy 10
Location Pt.1 x 899.95 y 980.19; Pt.2 x 1006.5 y 959.35
Supply Line Location x 896.21 y 982.86
● Free line
○ Vertical line
○ Horizontal line
☑ Irrigation sprinkler layout design
☑ Pipe hydraulic calculation
☑ Water application unformity cal...
X: 1,023.923 Y: 1,032.561
1:0 Saving Image

Figure 92 The guide for specifying mainline alignment

To create the sprinkler layout, the user clicks on the sprinkler layout button ①. Then, USUKU will create and draw the layout on the map ② as shown in Figure93.



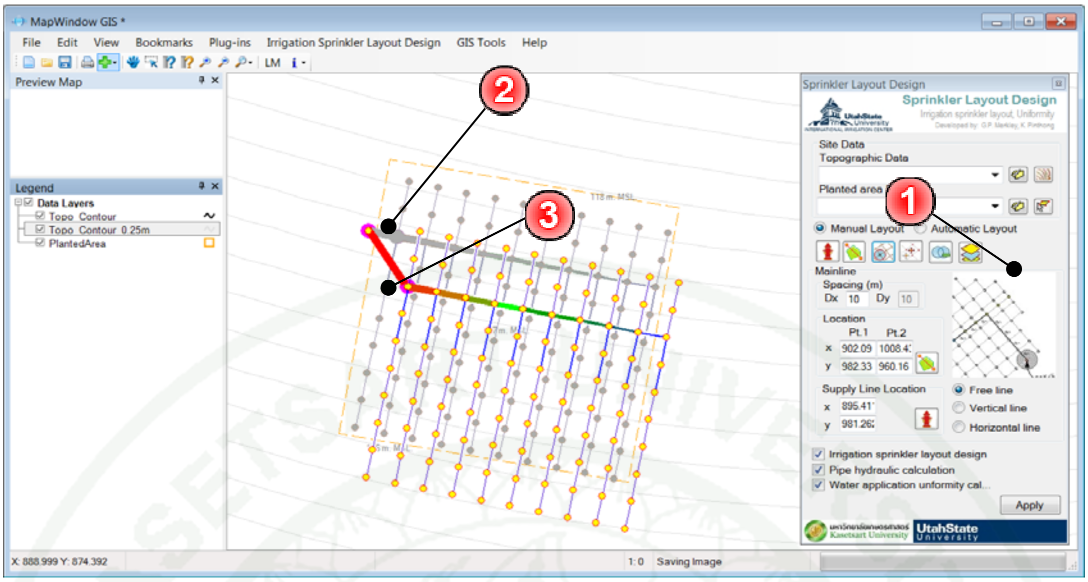
Site Data
Topographic Data: Topo
Planted area Data: PlantedArea
● Manual Layout ○ Automatic Layout
Spacing (m) Dx 10 Dy 10
Location Pt.1 x 899.95 y 980.19; Pt.2 x 1006.5 y 959.35
Supply Line Location x 896.21 y 982.86
● Free line
○ Vertical line
○ Horizontal line
☑ Irrigation sprinkler layout design
☑ Pipe hydraulic calculation
☑ Water application unformity cal...

Figure 93 Sprinkler layout creation process

In case the user wants to move or adjust the location of any sprinkler or pipe, he or she can click on the button ① and then click some location on map ② for a moving reference point, and finally clicking the new location.③ USUKU will then move all locations from the reference point to the new point as shown in the example in Figure94.

To create the irrigation sprinkler layout shape file, the user can click on button ①, then USUKU will create the node and line shape files, and add them to the design data project ② as shown in Figure95. The initial layout data can be shown in table form as either node (Table 7) or link data (Table 8).

At this point, the process for sprinkler layout generation is finished. The user can save the data and use it for the hydraulic model as described above.



Site Data
Topographic Data
Planted area

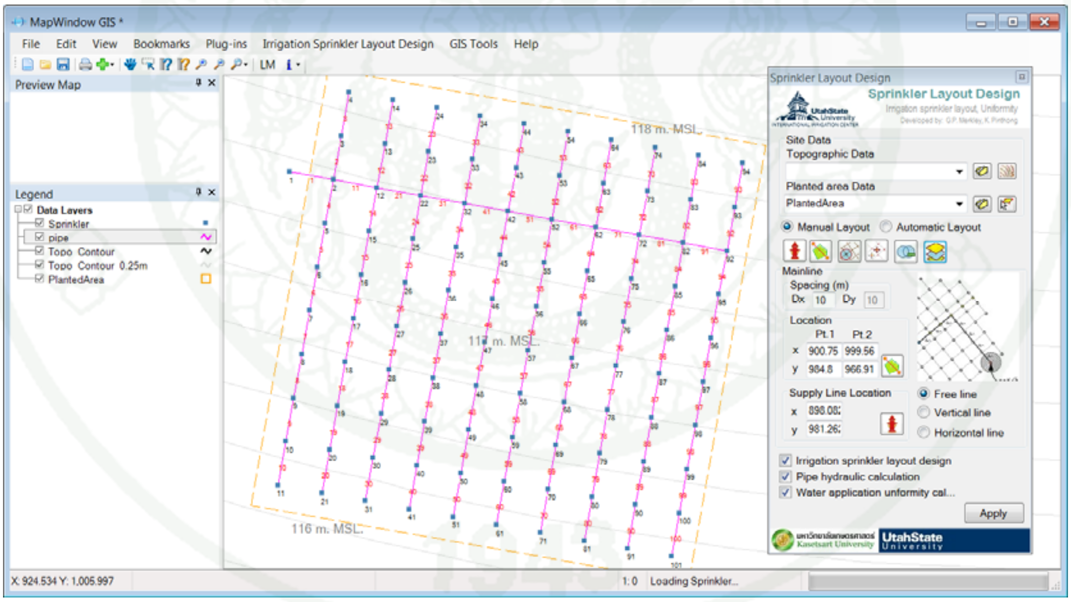
● Manual Layout ○ Automatic Layout

Mainline
Spacing (m) Dx 10 Dy 10
Location Pt.1 x 902.09 y 982.33; Pt.2 x 1008.4: y 960.16
Supply Line Location x 895.41' y 981.26:
● Free line ○ Vertical line ○ Horizontal line

☑ Irrigation sprinkler layout design
☑ Pipe hydraulic calculation
☑ Water application unformity cal...

X: 888.999 Y: 874.392 1:0 Saving Image

Figure 94 Sprinkler location moving process



Site Data
Topographic Data
Planted area Data: PlantedArea

● Manual Layout ○ Automatic Layout

Mainline
Spacing (m) Dx 10 Dy 10
Location Pt.1 x 900.75 y 984.8; Pt.2 x 999.56 y 966.91
Supply Line Location x 898.08: y 981.26:
● Free line ○ Vertical line ○ Horizontal line

☑ Irrigation sprinkler layout design
☑ Pipe hydraulic calculation
☑ Water application unformity cal...

X: 924.534 Y: 1,005.997 1:0 Loading Sprinkler...

Figure 95 Example of the final sprinkler layout results for a rectangular planted area

Table 7 Node and initial data

Node	X (m)	Y (m)	Z (m)	k_d	Type	Location
1	902.09	982.33	117.35	7.58E-05	Tank	U/S
2	911.88	980.29	117.40	7.58E-05	Junction	-
3	913.92	990.08	117.58	7.58E-05	R33	-
4	915.96	999.87	117.81	7.58E-05	R33	D/S
5	909.84	970.50	117.22	7.58E-05	R33	-
6	907.80	960.71	117.04	7.58E-05	R33	-
7	905.76	950.92	116.85	7.58E-05	R33	-
8	903.72	941.13	116.62	7.58E-05	R33	-
9	901.67	931.34	116.43	7.58E-05	R33	-
10	899.63	921.55	116.25	7.58E-05	R33	-
11	897.59	911.76	116.06	7.58E-05	R33	D/S
12	921.67	978.25	117.45	7.58E-05	Junction	-
13	923.71	988.04	117.63	7.58E-05	R33	-
14	925.75	997.83	117.85	7.58E-05	R33	D/S
15	919.63	968.46	117.27	7.58E-05	R33	-
16	917.59	958.67	117.08	7.58E-05	R33	-
..	..	..	..	..	..	..
..	..	..	..	..	..	..
97	993.86	932.55	116.79	7.58E-05	R33	-
98	991.82	922.76	116.60	7.58E-05	R33	-
99	989.78	912.97	116.41	7.58E-05	R33	-
100	987.74	903.18	116.22	7.58E-05	R33	-
101	985.70	893.39	116.03	7.58E-05	R33	D/S

Table 8 Link and initial data

id	Node From	Node To	Length (m)	Diameter (inch)	Area (cm^2)	C
1	1	2	10	6	0.000492	150
2	2	3	10	1	0.000492	150
3	3	4	10	1	0.000492	150
4	2	5	10	2	0.000492	150
5	5	6	10	2	0.000492	150
6	6	7	10	2	0.000492	150
7	7	8	10	2	0.000492	150
8	8	9	10	1	0.000492	150
9	9	10	10	1	0.000492	150
10	10	11	10	1	0.000492	150
11	2	12	10	6	0.000492	150
12	12	13	10	1	0.000492	150
13	13	14	10	1	0.000492	150
14	12	15	10	2	0.000492	150
15	15	16	10	2	0.000492	150
16	16	17	10	2	0.000492	150
..	..	..	..	..	..	..
..	..	..	..	..	..	..
97	97	98	10	2	0.000492	150
98	98	99	10	1	0.000492	150
99	99	100	10	1	0.000492	150
100	100	101	10	1	0.000492	150

3.Automatic sprinkler layout design

With automatic layout design, USUKU only needs three parameters: (1) water supply location; (2) topographic data; and, (3) planted area shape (currently restricted to rectangular shapes). After the user has loaded the required parameters into the MapWindow legend the layout and hydraulic calculations can begin. USUKU uses a topology of mainline alignment database to make a guide for line alignment. Then, the alignment is used to compute a suitable sprinkler layout as shown in the pseudo code of Figure96.

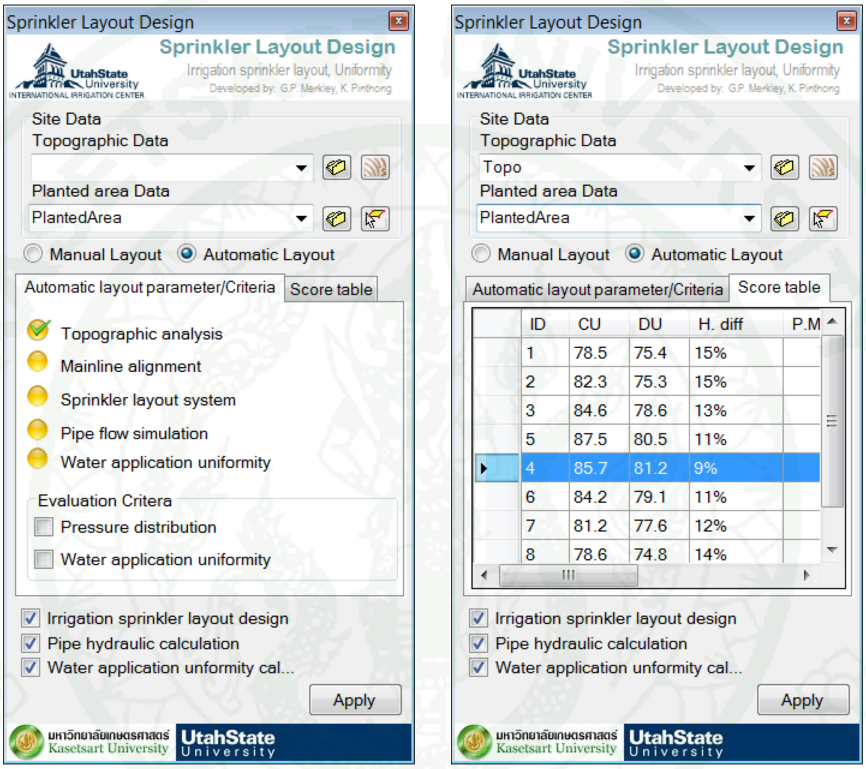
```
      //Basic design data
       Initial population for pipe size
repeat
        create Sprinkler location
       //(node that due to the condition of mainline alignment)
 Create link
       //Link All node
 Modify links //(pipe system)
       Use Dijstra algorithm for all path-flow
      //from all node to tank node
       Use Hydraulic model for simulate pipe hydraulic properties
       Use the hydraulic pressure from hydraulic model result for
 compute a water application uniformity
       Evaluate mainline
       if Okay then
        COMMAND = STOP
       if NOT okay then
       adjust the new mainline alignment
      //(base one guide of line alignment)

untilCOMMAND = STOP
      //Return a optimum pipe size
 Report a selected mainline alignment
```

Figure 96 Pseudo code for semi-automatic mainline layout process.

In case the planted area is located on a topography that needs more than one mainline, USUKU will display a message to the user to decide upon a split, or to divide the field shape. This is because the current version of USUKU can work with data that have only one mainline guide per planted area. That means that in this case it is necessary to compute the number of planted areas and to divide the field into subareas.

USUKU will create a many layouts for the planted area and evaluate each of them separately. The layout and evaluation value (CU/DU and pressure distribution) are shown in Figure97. The user can select one of these, and can manually modify it, if desired.



	ID	CU	DU	H. diff	P.M
	1	78.5	75.4	15%	
	2	82.3	75.3	15%	
	3	84.6	78.6	13%	
	5	87.5	80.5	11%	
▶	4	85.7	81.2	9%	
	6	84.2	79.1	11%	
	7	81.2	77.6	12%	
	8	78.6	74.8	14%	

Figure 97 Sample results from the automatic layout design process

4. Case studies

The USUKU model was tested with two applications for assessing whole-field sprinkler irrigation application uniformity, and an irrigation sprinkler layout system design. The details of the study are presented below.

A. Assessing Whole-Field Sprinkler Irrigation Application Uniformity

A whole-field sprinkler irrigation application uniformity study has the objective of determining the relationships between sprinkler properties. This experiment has three sprinkler types for testing, including the Nelson R33, Nelson R33LP (low pressure) and Rainbird Mini Paw/LG-3. All three sprinklers were tested by (Zhang 2010) at the Utah Water Research Laboratory . The details for the relationship between sprinkler nozzle and discharge are shown in Table 9.

Table 9 Pressure versus flow rate equations for the tested sprinklers

Sprinkler type	Sample 1	Sample 2	Sample 3	manufacturer's information
Nelson R33	$q=88.8h^{0.5}$	$q=87.8h^{0.5}$	$q=87.9h^{0.5}$	$q=87.6h^{0.5}$
Nelson R33LP	$q=86.9h^{0.5}$	$q=86.8h^{0.5}$	$q=86.8h^{0.5}$	$q=87.1h^{0.5}$
Rainbird Mini Paw/LG-3	$q=30.2h^{0.5}$	$q=29.6h^{0.5}$	$q=27.8h^{0.5}$	$q=31.9h^{0.5}$

Note: q is flow rate (lph); and, h is sprinkler pressure (kPa).

1. Basic data design and irrigation project condition

Topography data for this case is a level field (no slope). The planted area size is 250 x 400 m (Figure 98). The mainline is located parallel to the planted area at the middle of long edge of the field. The main variables for this study include: three sprinkler types, seven water supply pressures, and seven sprinkler spacings (four square spacing + three rectangular spacing). There were 147 cases.

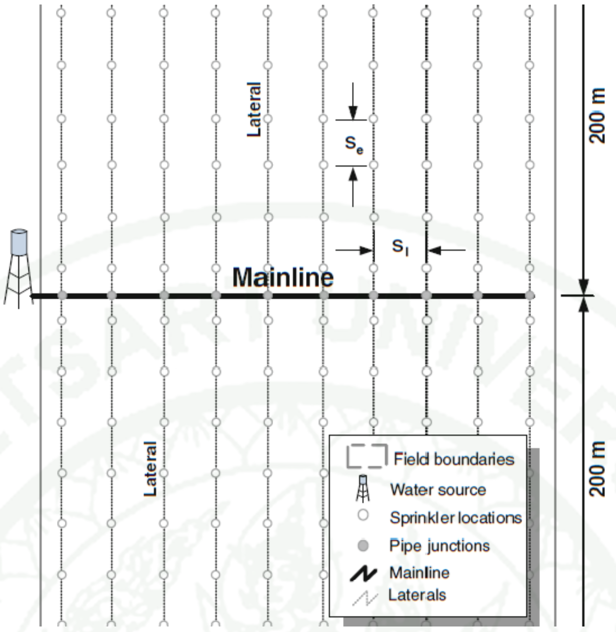


Figure 98 Plan view of the rectangular field

2. Study results

The main result of this study was water application uniformity that can be shown in detail for any case, such as pressure map, pipe details, and CU values. Some examples are shown in Figures99 and 100. For all cases, the comparison shows a relationship between sprinkler spacing and pressure for each sprinkle type. The results show that both of the Nelson sprinklers have better performance in terms of uniformity, compared to the Rainbird, as shown in Figure101. However, when comparing the sprinkler spacing for a given sprinkler type, it was found that a square spacing is better than rectangular spacing, and a spacing of 12 x 12 m gives the best uniformity for the Nelson sprinklers. But for the Rainbird Mini Paw/LG-3 the best spacing is 8 x 8 m. The reason is that the Rainbird Mini Paw/LG-3 has a smaller dischargethan the Nelson sprinklers at any given pressure, as shown in Figures102 to 104.

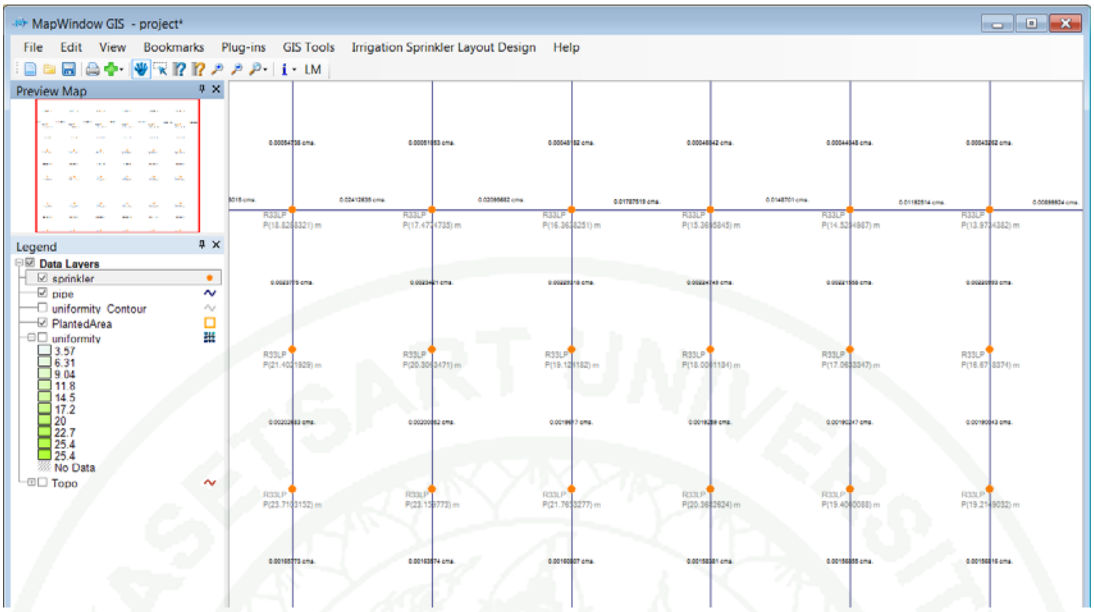


Figure 99 Pipe size and pressure calculation results

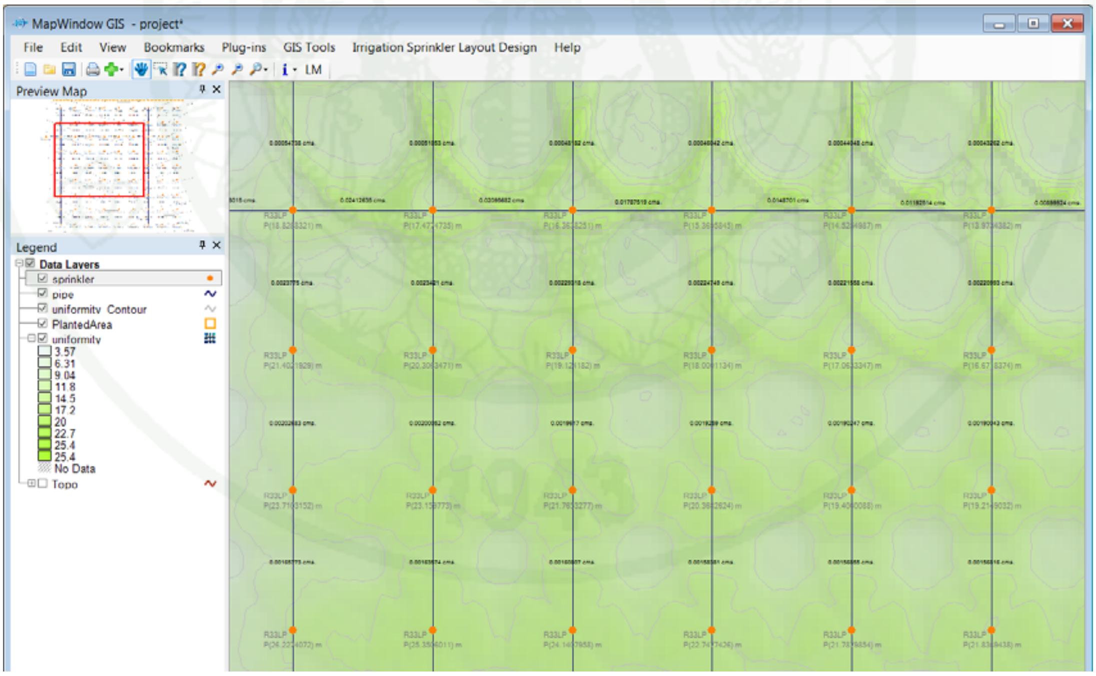
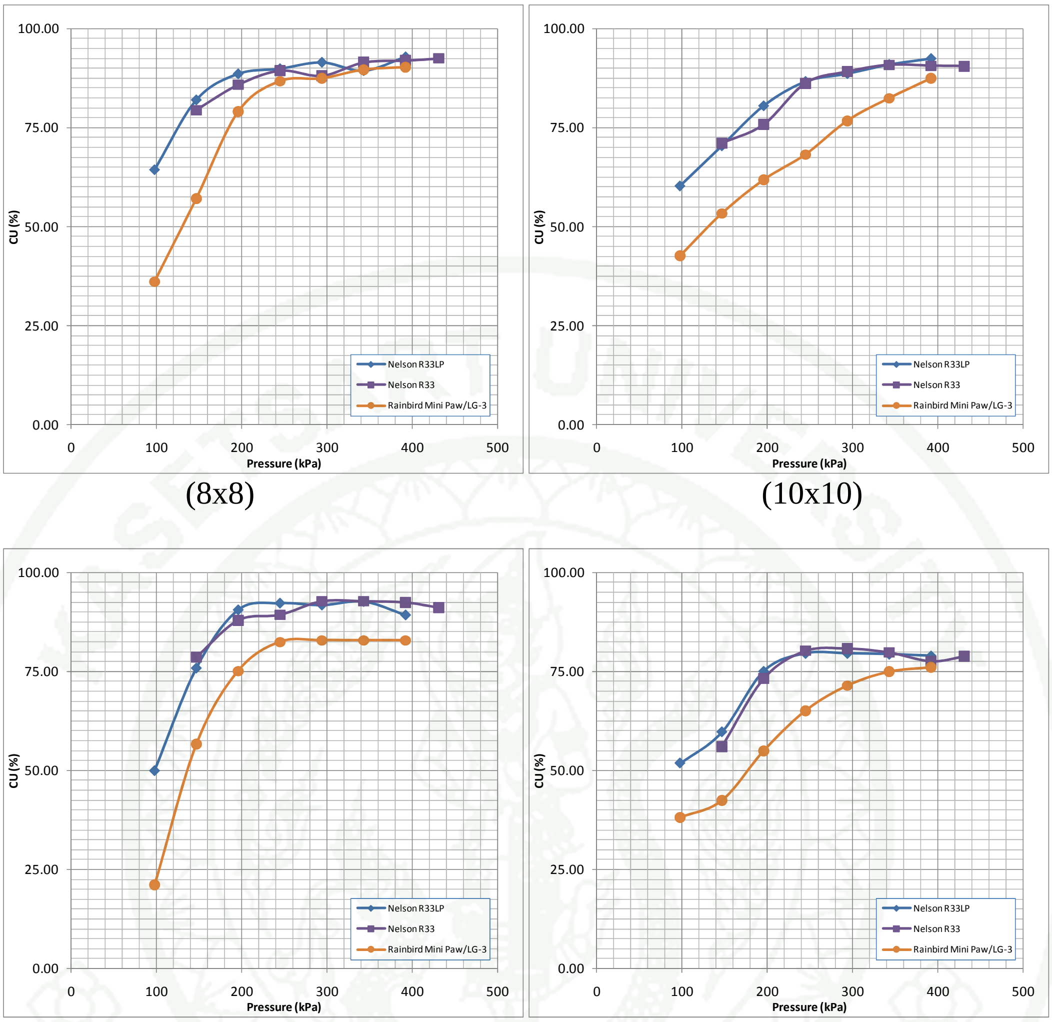


Figure 100 Water application map results



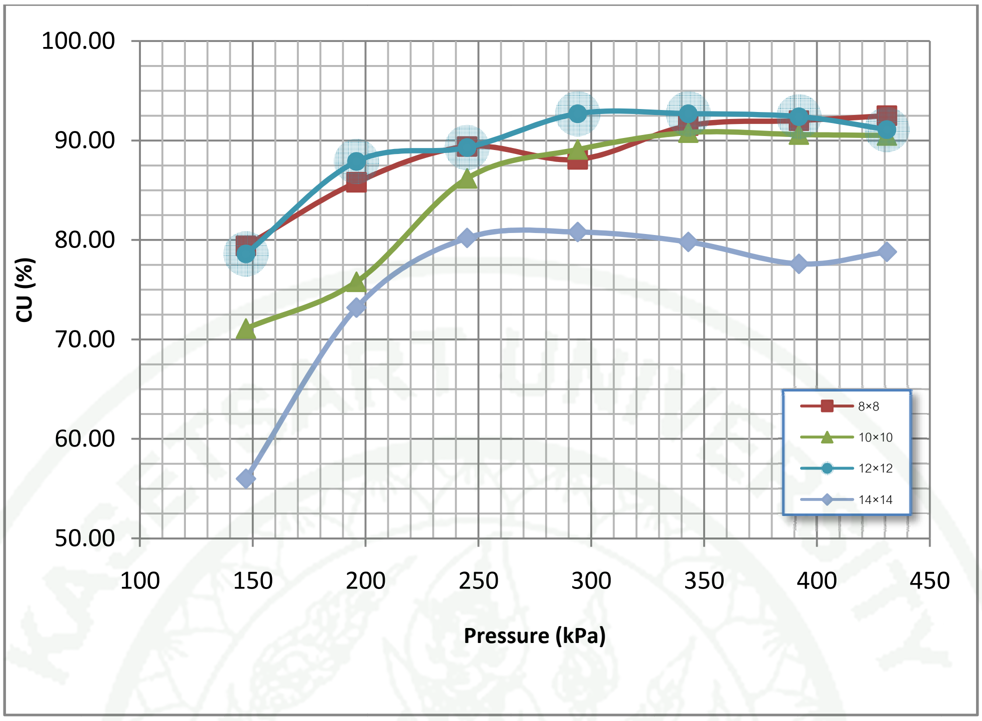
(8x8)

(10x10)

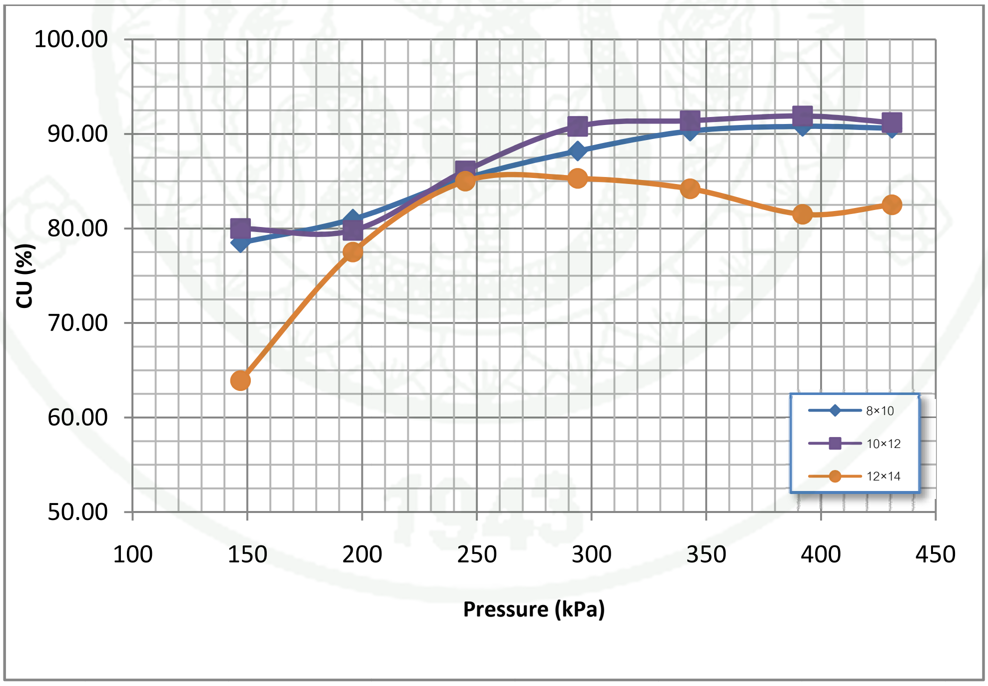
(12x12)

(14x14)

Figure 101 Sprinkler type, pressure and spacing relationships

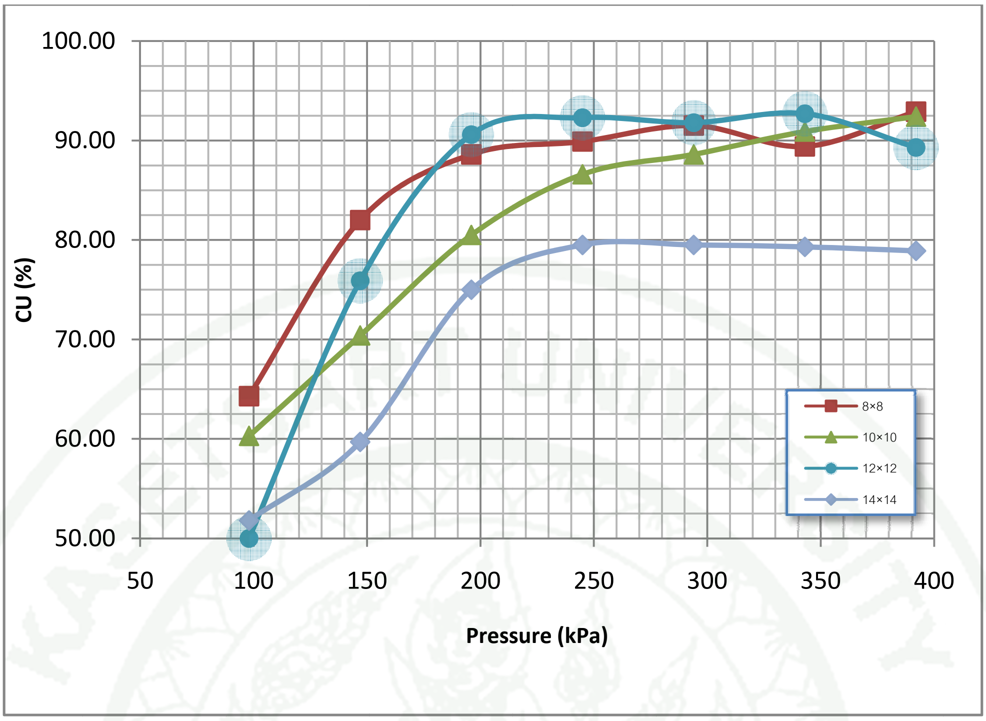


(Square spacing)

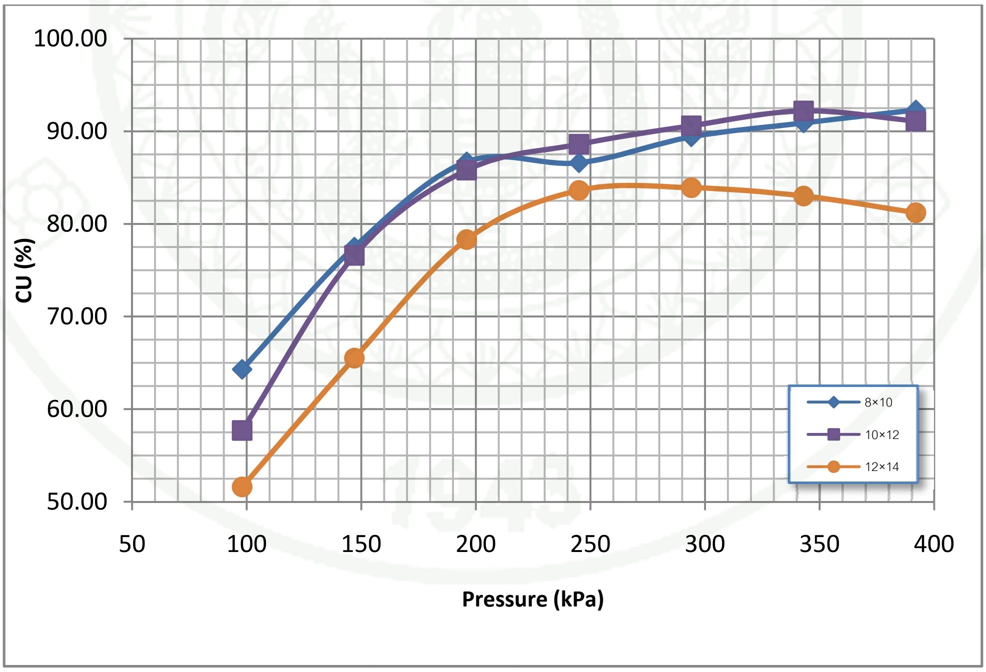


(Rectangular spacing)

Figure 102 Relationship between pressure and spacing for the Nelson R33 sprinkler

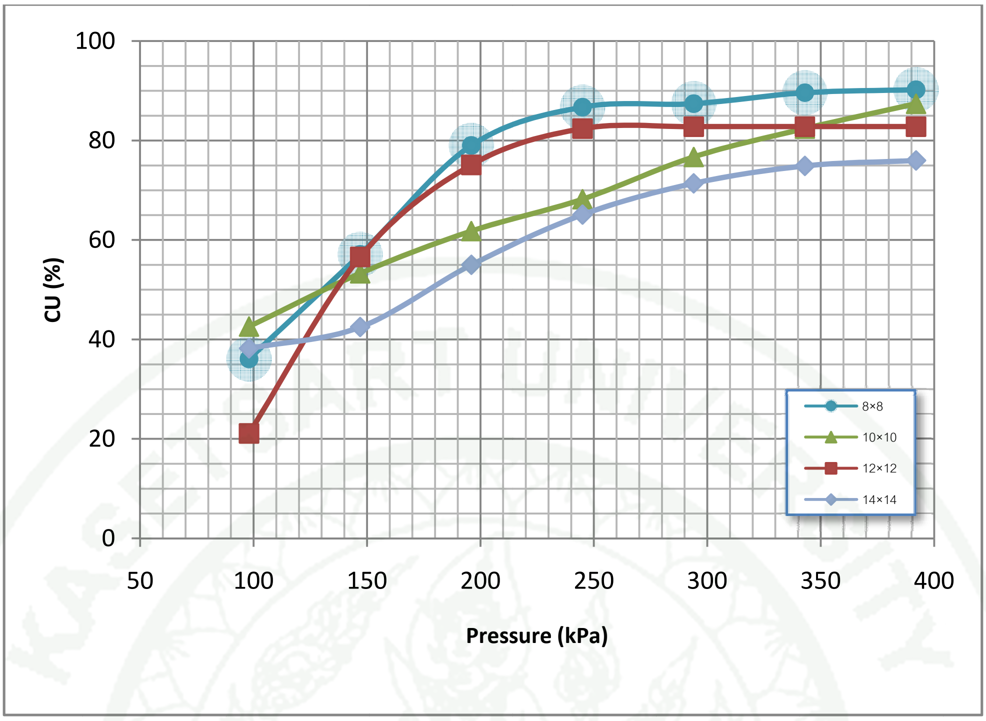


(Square spacing)

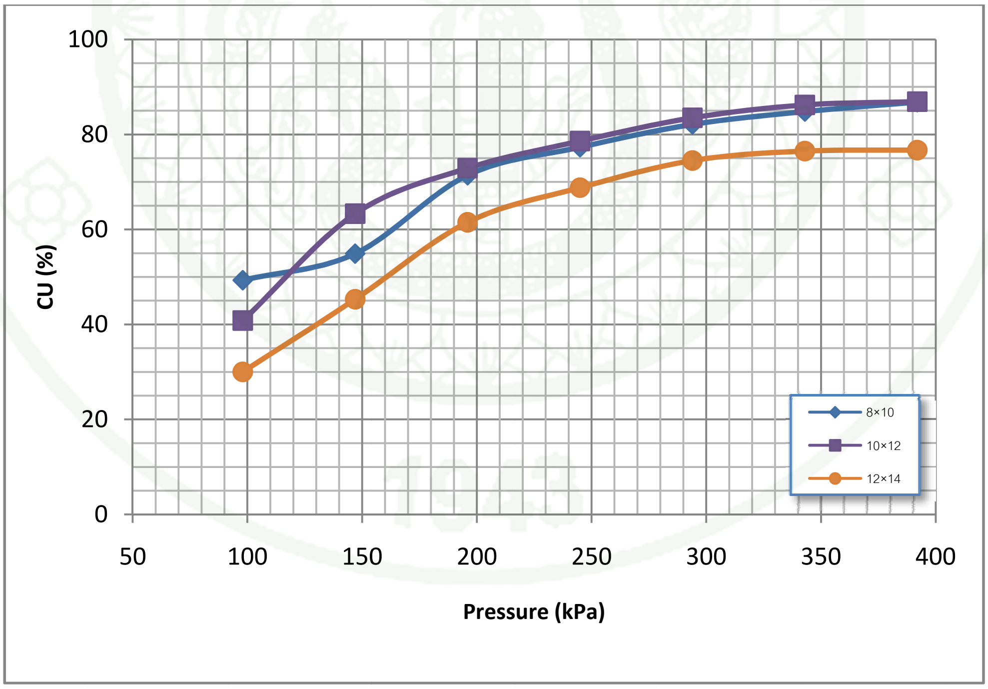


(Rectangular spacing)

Figure 103 Relationship between pressure and spacing for the Nelson R33LP sprinkler



(Square spacing)



(Rectangular spacing)

Figure 104 Relationship between pressure and spacing for the Rainbird Mini Paw/LG-3 sprinkler

B. Topography analysis for a suitable mainline guide

The topographic analysis for USUKU was created to analyze a suitable mainline guide for the user to create a sprinkler layout. The planted area shape depends on the farm owner's properties. Sometimes, it’s located on a flat area ①, one side of a slope ②, two sides of a slope ③ ,or more than two hill slopes④ as shown in Figure105. A topography analysis will use topography data and planted area shape to analyze for a suitable mainline guide of the planted area. In some cases, the planted area is greater than that which can be served by a single mainline. In such cases, USUKU will tell the user that it is necessary to split the planted area, as described above.

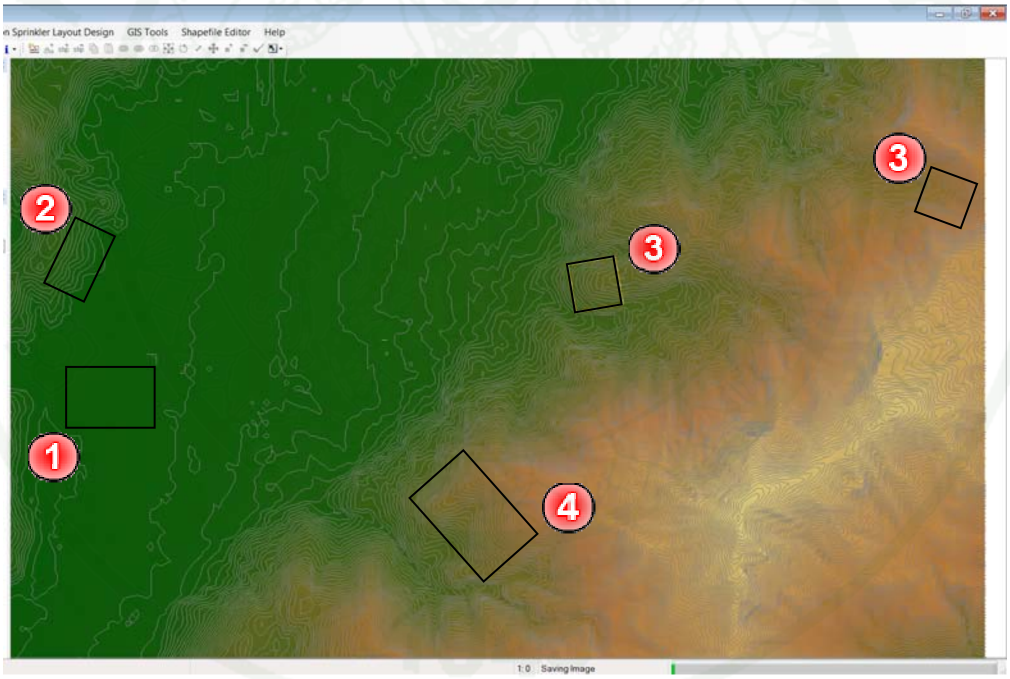


Figure 105 Various planted area locations overlaid on a topographic map

1. One mainline with two side down-hill case

In some cases the planted area is located on two sides of a hill, as shown in Figure106. The topographic analysis will search for a profile that parallels the widest side and the longest side, as shown in Figures107 and 108.

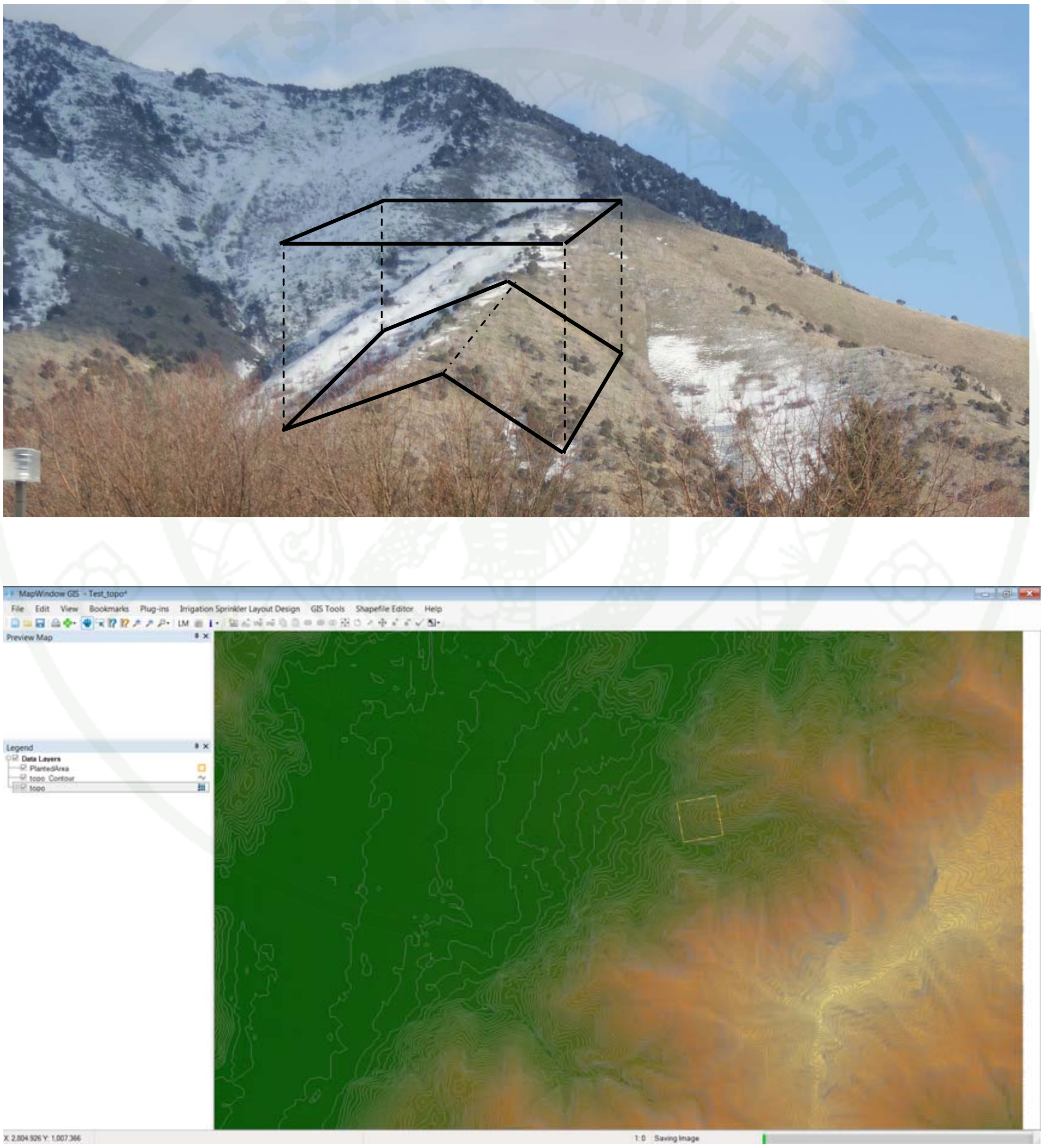
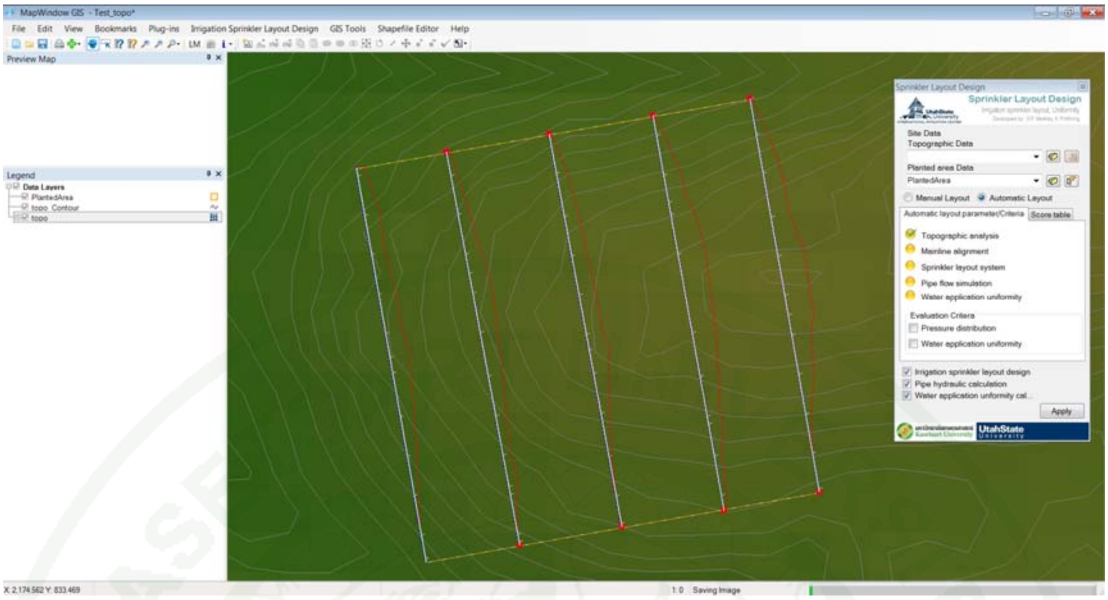


Figure 106 A planted area located on two sides of a hill slope



Sprinkler Layout Design

Site Data

Topographic Data

Planted area Data: PlantedArea

○ Manual Layout ● Automatic Layout

Automatic layout parameter/Criteria | Score table

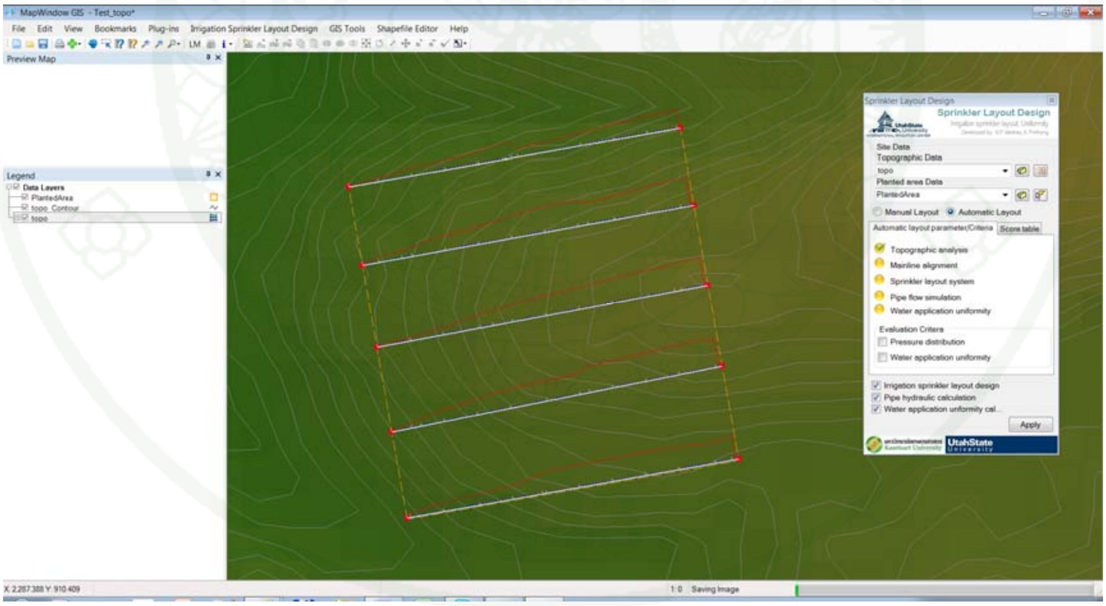
- ✓ Topographic analysis
- ● Mainline alignment
- ● Sprinkler layout system
- ● Pipe flow simulation
- ● Water application uniformity

Evaluation Criteria

- ☐ Pressure distribution
- ☐ Water application uniformity

- ☑ Irrigation sprinkler layout design
- ☑ Pipe hydraulic calculation
- ☑ Water application uniformity cal...

Figure 107 Profile of the widest side of a planted area



Sprinkler Layout Design

Site Data

Topographic Data: topo

Planted area Data: PlantedArea

○ Manual Layout ● Automatic Layout

Automatic layout parameter/Criteria | Score table

- ✓ Topographic analysis
- ● Mainline alignment
- ● Sprinkler layout system
- ● Pipe flow simulation
- ● Water application uniformity

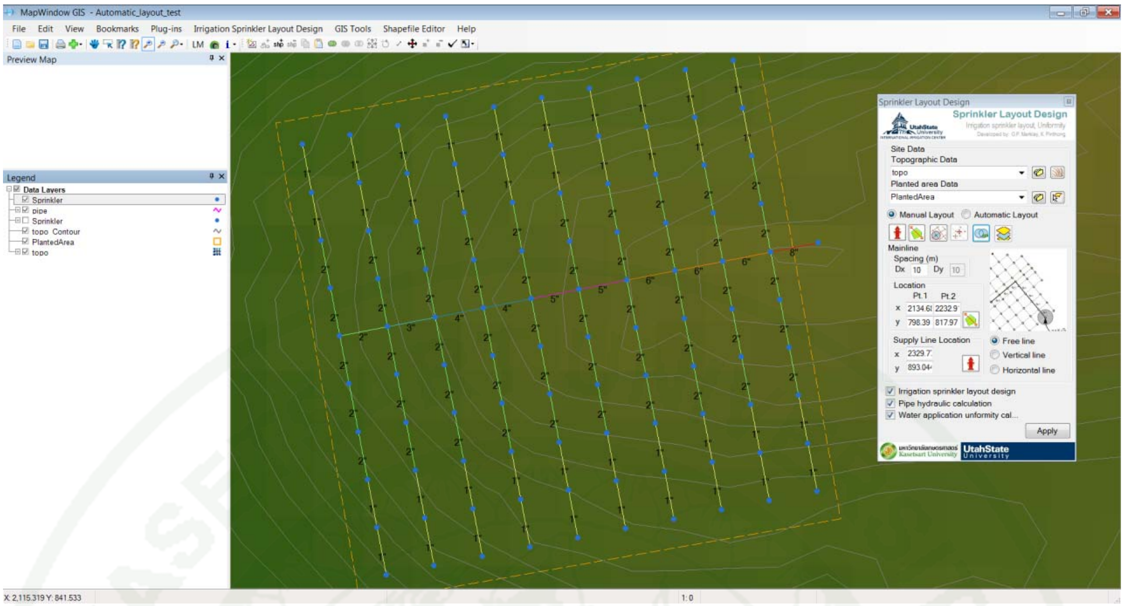
Evaluation Criteria

- ☐ Pressure distribution
- ☐ Water application uniformity

- ☑ Irrigation sprinkler layout design
- ☑ Pipe hydraulic calculation
- ☑ Water application uniformity cal...

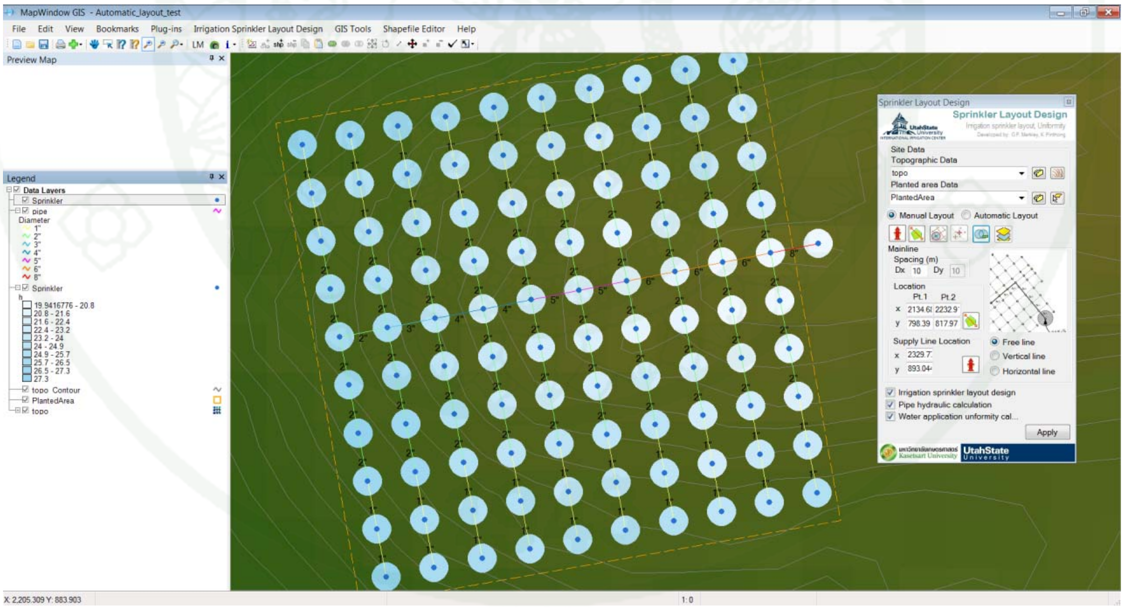
Figure 108 Profile of the longest side of planted area

The topographic analysis results for the planted area will determine a suitable mainline that lays along the middle of the long side, and the hydraulic results and water application uniformity are as shown in Figures109 - 111.



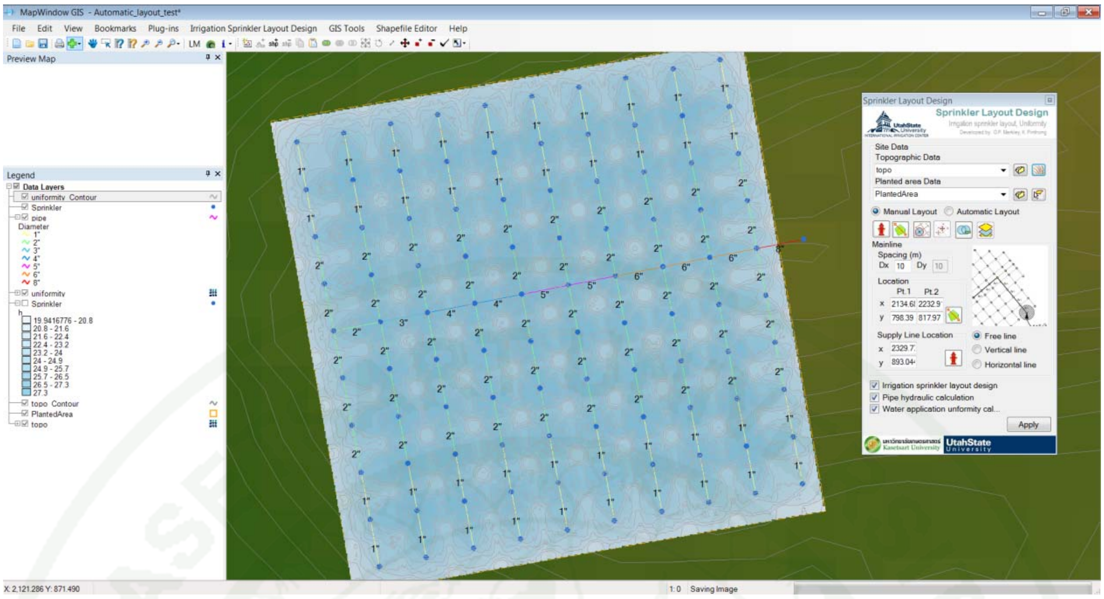
Topographic Data: topo
Planted area Data: PlantedArea
● Manual Layout ○ Automatic Layout
Spacing (m) Dx 10 Dy 10
Location Pt.1 x 2134.6 y 798.39; Pt.2 x 2232.9 y 817.97
Supply Line Location x 2329.7 y 893.04
● Free line
○ Vertical line
○ Horizontal line
☑ Irrigation sprinkler layout design
☑ Pipe hydraulic calculation
☑ Water application unformity cal...

Figure 109 Irrigation sprinkler layout results



Topographic Data: topo
Planted area Data: PlantedArea
● Manual Layout ○ Automatic Layout
Spacing (m) Dx 10 Dy 10
Location Pt.1 x 2134.6 y 798.39; Pt.2 x 2232.9 y 817.97
Supply Line Location x 2329.7 y 893.04
● Free line
○ Vertical line
○ Horizontal line
☑ Irrigation sprinkler layout design
☑ Pipe hydraulic calculation
☑ Water application unformity cal...

Figure 110 Pressure distribution map results

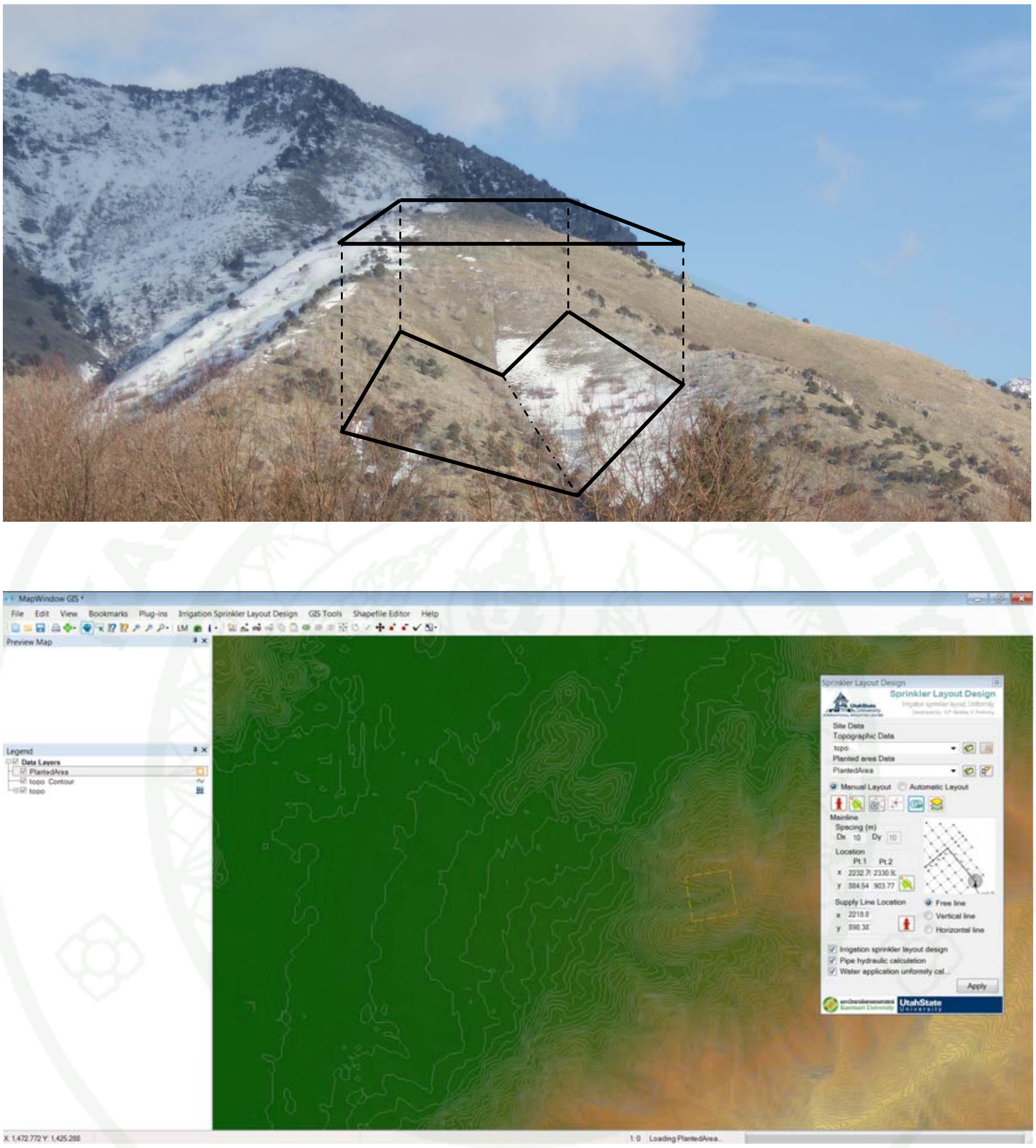


Topographic Data: topo
Planted area Data: PlantedArea
● Manual Layout ○ Automatic Layout
Spacing (m) Dx 10 Dy 10
Pt.1 x 2134.6 y 798.39
Pt.2 x 2232.9 y 817.97
Supply Line Location x 2329.7 y 893.04
● Free line ○ Vertical line ○ Horizontal line
☑ Irrigation sprinkler layout design
☑ Pipe hydraulic calculation
☑ Water application unformity cal...

Figure 111 Water application uniformity map results

2. Two mainlines with two downhill slopes

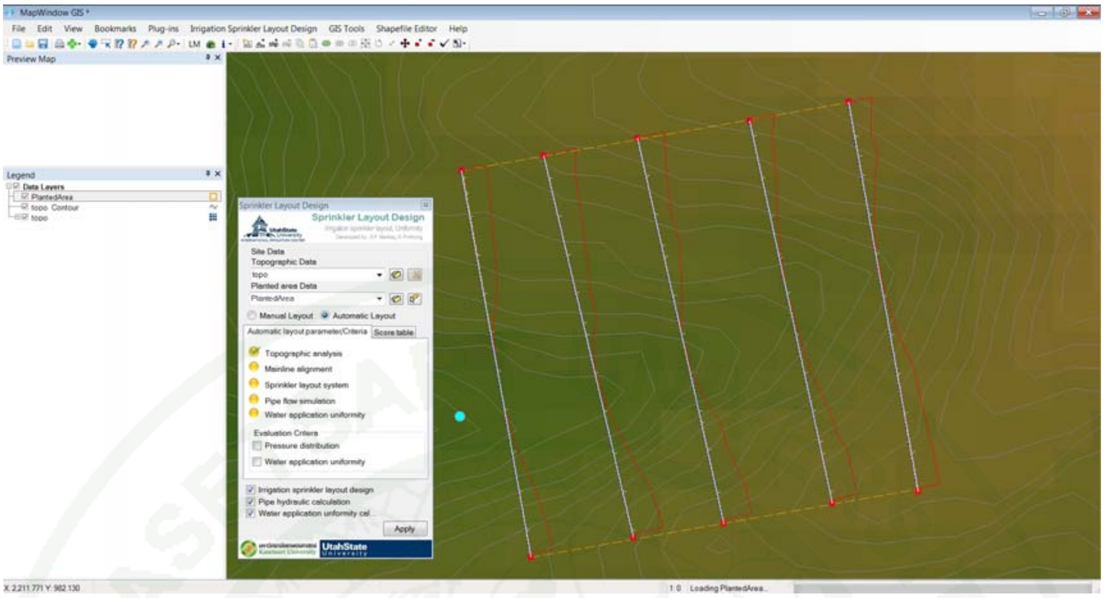
For this case, the planted area is located on two downhill slopes that run from two hills to a creek that closely parallel one side of the planted area (Figure110). For this case one side of the planted area has profile like a V shape (Figure111) and the perpendicular side has a linear slope profile (Figure112);this means that this planted area needs two mainlines and should be split into two parts.



Site Data
Topographic Data: topo
Planted area Data: PlantedArea
● Manual Layout ○ Automatic Layout
Mainline
Spacing (m) Dx 10 Dy 10
Location Pt.1 x 2232.7 y 884.54; Pt.2 x 2330.9 y 903.77
Supply Line Location x 2218.8 y 896.38
● Free line
○ Vertical line
○ Horizontal line
☑ Irrigation sprinkler layout design
☑ Pipe hydraulic calculation
☑ Water application uniformity cal...

X: 1,472.772 Y: 1,425.288
1:0 Loading PlantedArea...

Figure 112 A planted area located on two downhill slopes with a low-elevation seam between them

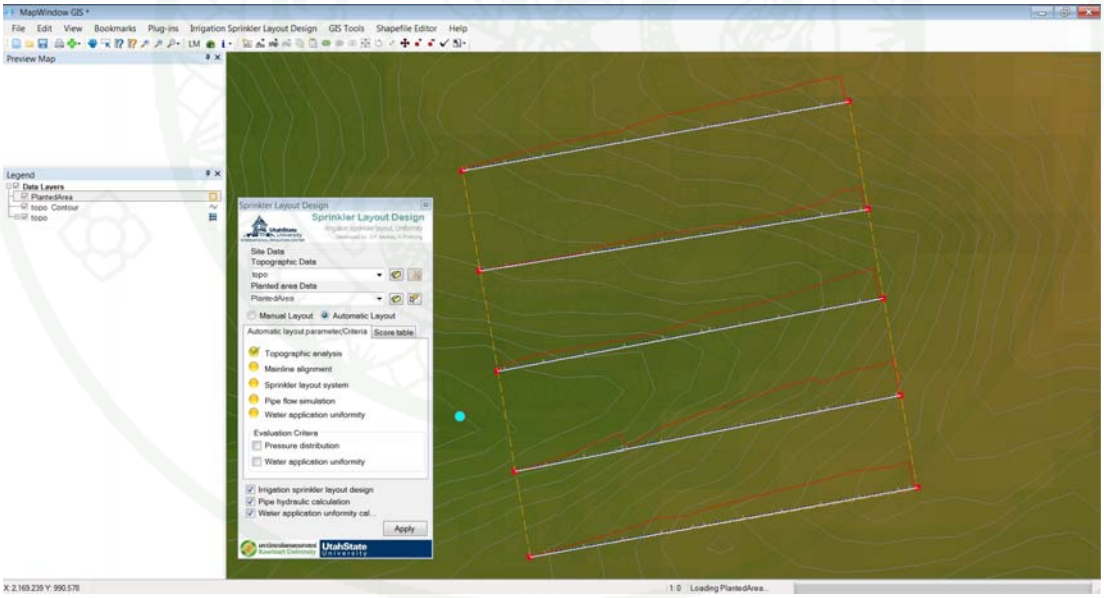


Site Data
Topographic Data: topo
Planted area Data: PlantedArea
○ Manual Layout ● Automatic Layout
Automatic layout parameter/Criteria
- ✓ Topographic analysis
- ● Mainline alignment
- ● Sprinkler layout system
- ● Pipe flow simulation
- ● Water application uniformity

Evaluation Criteria
- ☐ Pressure distribution
- ☐ Water application uniformity

- ☑ Irrigation sprinkler layout design
- ☑ Pipe hydraulic calculation
- ☑ Water application uniformity cal...

Figure 113 A planted area with an approximately V-shape profile



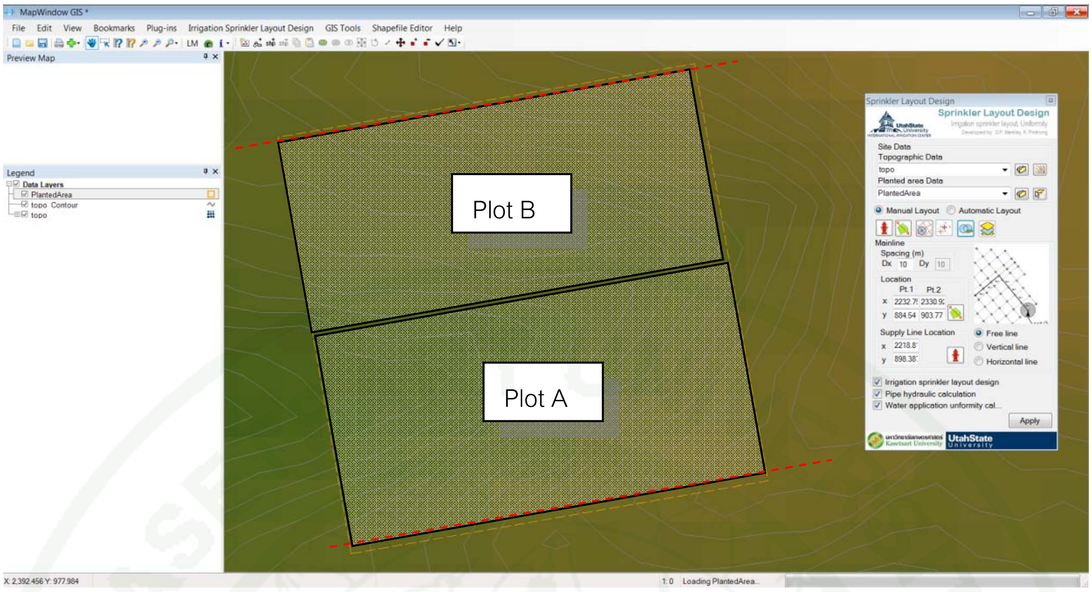
Site Data
Topographic Data: topo
Planted area Data: PlantedArea
○ Manual Layout ● Automatic Layout
Automatic layout parameter/Criteria
- ✓ Topographic analysis
- ● Mainline alignment
- ● Sprinkler layout system
- ● Pipe flow simulation
- ● Water application uniformity

Evaluation Criteria
- ☐ Pressure distribution
- ☐ Water application uniformity

- ☑ Irrigation sprinkler layout design
- ☑ Pipe hydraulic calculation
- ☑ Water application uniformity cal...

Figure 114 A planted area with an approximately linear slope profile

In this case, USUKU will report to the user that the planted area should be divided into two parts (Figure115), whereby the user can use the sprinkler layout tool, hydraulic model, and water application tool to perform the sprinkler irrigation process as described above (Figure116).



Site Data
Topographic Data: topo
Planted area Data: PlantedArea
● Manual Layout ○ Automatic Layout
Mainline
Spacing (m) Dx 10 Dy 10
Location

	Pt.1	Pt.2
x	2232.7	2330.9
y	884.54	903.77

Supply Line Location
x 2218.8
y 898.38
● Free line
○ Vertical line
○ Horizontal line
☑ Irrigation sprinkler layout design
☑ Pipe hydraulic calculation
☑ Water application unformity cal...

Figure 115 A planted area divided by a split line

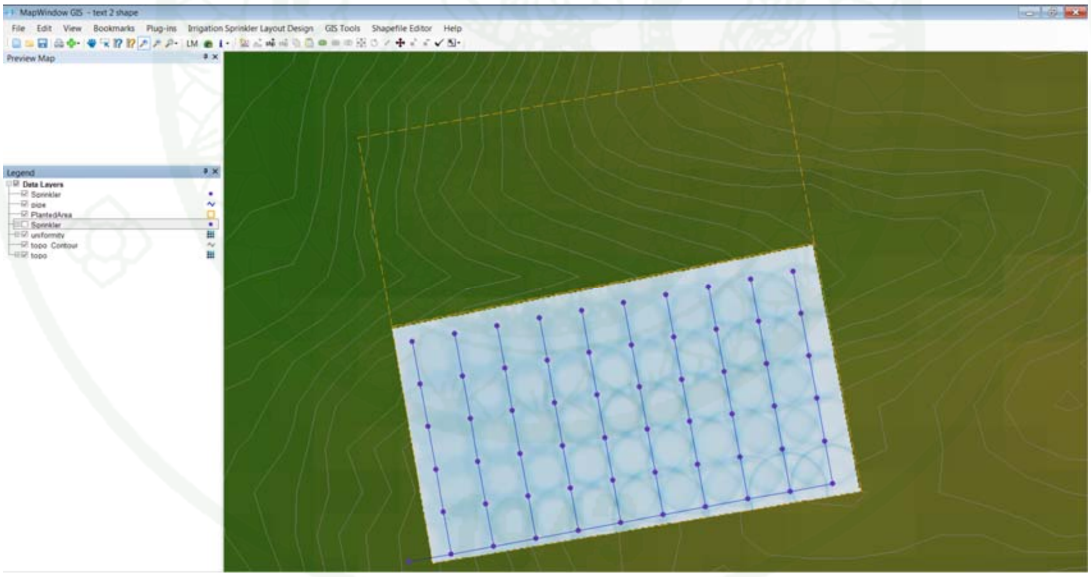


Figure 116 Sample hydraulic results and water uniformity map for part A

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The main objective this research wassolid-set sprinkler layout software development, and the USUKU model was developed with a GIS interface (Mapwindow Plug-in) for integrating: (1) water application uniformity; (2) a pipe hydraulic model; and, (3) irrigation sprinkler pipe system layout. The conclusions canbe drawn as follows:

1. Water application uniformity modulefor USUKU used for two main objectives are: (1) for existing projects by evaluating water application uniformity based on field measurements;and,(2) for designing a new sprinkler system by evaluating the expected water application uniformity as calculated from a hydraulicanalysis. Both evaluation results can be presented in a water application contour map, and manifested as coefficient of uniformity (*CU*)or distribution coefficient (*DU*).

2. The pipe hydraulic module for USUKU is branch hydraulic model that based on a gravity-fed concept and was specifically developed for sprinkler or trickleirrigation.The golden section search method was applied in the model by balancing pressures from each branch end node to junctions, and finally to the water supply source. The Dijkstra algorithm is used to create flow paths from the water source to all nodes ("one to all"). The flow accumulationcan be created by duplicate path links. Suitable pipe sizes are automatically selected by pipe velocity criteria and calculated pipe hydraulic losses. Hydraulic results canbe presented as a pressure map or a table of pipe properties. The results are usedto evaluate the pressure distribution in a pipe system and for a water application uniformity model as mentioned above.

3. The irrigation sprinkler pipe system layout module for USUKU is a pipe layout editor. This is usedto createpipe layout data for the hydraulic module and water application module. The results of the hydraulic module and water application module

are used to evaluate and select the available pipe layouts for topography and planted shape. USUKU usesthe amainline guide to create a rectangular spacing of sprinkler positions. The mainline guide can be placed manually by the designer, or it can be placed automatically by the topographic analysis module. A point in the polygon algorithm is applied for a selected sprinkler in the planted area. The Delaunay algorithms are usedto create initial pipe linking, and then they use the Dijkstra algorithm again to create the actual paths from the supply source to all sprinkler nodes. After that, the module creates two shape files (Node.shp and Link.shp) for evaluation by the hydraulic module and water application uniformity module. In additional, USUKU has a utility for the sprinkler layout editor such as a sprinkler editor (add, delete, move location of sprinkler, or assign sprinkler properties, etc), planted area editor, and topography tool (data transform xyz data to grid, grid data to contour shapefile).

4. USUKU was tested with two cases:(1) assessing whole-field sprinkler irrigation application uniformity, and, (2) topography analysis for a suitable mainline guide. In both case studies USUKU was able togenerate good results for sprinkler irrigation system design. In conclusion, the USUKU modules and interface arebased on basic site data, including topography, planted area shape, and supply source location. The sprinkler irrigation designer spends only a few minuteson layout design. And the design results can be usedto create a draft sprinkler layout drawing, bill of quantities and details too.

Recommendations

1. Catch cans for storing water application overlapping data of water application uniformity computation process use grid data in theESRI grid file format. For large field sizes, the number of grid or catch-can spacing increases. For example, for a field width of100 m and a field length of100 m,and a can spacing of 1 m, there will be10,000 grid points. This is significant because the more grid points, the more computational expense in the model. Because the computation loop for overlapping is equal to number of gridline multiplied by number of sprinklers, and in terms of

uniformity computation, the number of calculation loops is greater than the factorial of the number of grid points (10,000!, in the above example). Thus, a new version of the model should decrease the number of sorting loops by usinga more efficient sorting technique.

2. The type of water supply source for pipe hydraulic model in USUKU is a tank or constant-head control type. Thus, a pump should be included as one type of water source. And the model concept is based on solid-set sprinklers in which all sprinklers operate simultaneously over the entire planted area. This concept is most feasible for a small planted area. Consequently, the model should be modifiedfor individual lateral computations corresponding to a periodic-move sprinkler system. In addition, this would permit application of the model to hand-move sprinkler system designs.

3. The irrigation sprinkler pipe system layout function only with first of the polygon shapes in a planted area shape file. In case of topography analysis resultswhich havemore than one mainline,currently the program needs to split a planted shape to sub-shapes before creating the sprinkler layout, and then separately evaluate the layout for each sub-area. So, the layout module should be modifiedto support multiplemainline guides, with corresponding generalizations to the pipe system layout evaluation process.

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2nd prize in Thailand ICT Award, ICT EXPO 2005 "**Web-Based Vehicle Routing**"

3th prize in Logistic Software Contest 2004 "**Forming Batches of Customer Orders in a Warehouse**"