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**NUTRIENT SOLUTION MANAGEMENT
FOR GREENHOUSE TOMATOES:
A MULTIPLE-CASE STUDY**



A thesis presented in partial fulfilment of the requirements
for the degree of Master of Applied Science
at Massey University, Palmerston North,
New Zealand

Minhua Xu

2006

**NUTRIENT SOLUTION MANAGEMENT
FOR GREENHOUSE TOMATOES:
A MULTIPLE-CASE STUDY**

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2006

MASSEY UNIVERSITY
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Abstract

Nutrient solution released from hydroponic greenhouse operations has been considered as a potential pollution source by New Zealand regional authorities. *The Management of Nutrient Solutions Released from Greenhouses: A Code of Practice* (COP) is designed to assist New Zealand greenhouse growers in managing nutrient solution release in hydroponic systems to comply with The Resource Management Act 1991 (RMA) and regional resource plans prepared by regional authorities to ensure that their constituents act appropriately.

A multiple-case study was designed to investigate the nutrient solution management and disposal practices of New Zealand hydroponic greenhouse tomato growers and, further, to investigate whether or not these practices meet the guidelines set out in *The Management of Nutrient Solutions Released from Greenhouses: A Code of Practice*.

Three hydroponic greenhouse properties that represent the current New Zealand greenhouse tomato industry were selected as case studies. How the greenhouse growers manage nutrient solution in these greenhouses was investigated by interviewing the growers. The results show that none of the case study growers fully met the guidelines given in the COP. However, recirculating growers manage nutrient solution better than do the run-to-waste grower in terms of reducing nutrient solution discharge frequency. They release less volume of nitrogen into the environment per 1000 kg of tomato produced in their recirculating growing systems. The research results indicate that high-technology recirculating grower could better satisfy the requirements set out in the COP. Low-technology run-to-waste growers are unlikely to meet those requirements due to their system design. Therefore, adopting a recirculating growing system is considered as a trend of the industries in the future.

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1. Introduction

1.1 Background

Greenhouse systems can efficiently produce high-quality products for consumers. As a result, in the last decade, worldwide commercial greenhouse production has expanded rapidly (RIRDC, 2001). These systems are found predominantly in affluent countries that have discerning consumers or countries that have access to such markets (RIRDC, 2001). New Zealand is one of these countries. Major crops in greenhouses include tomatoes, cut flowers, strawberries, capsicums, cucumbers, and lettuces (MAF, 2002).

Tomatoes are a significant greenhouse crop in New Zealand. In 2004, tomatoes were ranked number one in terms of household spending in *Statistics New Zealand's Ranking of Household Expenditure* for the top 30 fresh vegetables (Vegfed, 2005). Consumers spend \$118 million on tomatoes annually. This was more than double the 1996 figure (\$55.5 million) (Vegfed, 2005). Similarly, New Zealand's export of greenhouse tomatoes has also increased. In 2002, the value of export greenhouse tomatoes was \$1.4 million. By 2003, it had increased more than three times to \$4.9 million and by 2005 to \$7.5 million (Ivicevich, 2005). In 2005, 40,000 tonnes of greenhouse tomatoes were supplied to the domestic market (worth \$97.5 million) and 2,000 tonnes were exported (HortNZ, 2006). Most of the fresh market tomatoes in New Zealand are produced in greenhouses (HortNZ, 2006). In 2005, 375 commercial growers produced tomatoes from 120 hectares of greenhouses (HortNZ, 2006). The majority of these are located in the North Island, and one-third in the Auckland region (HortNZ, 2006).

In the last decade in this scene of expanding consumption and export, New Zealand greenhouse growers' production technology has significantly improved. This has been represented by improvements in growing systems and hence in increased yield. Traditionally, greenhouse properties in New Zealand have been small (0.5-1.0 hectare) family-run greenhouses. Some growers produced tomatoes in soil (Vegfed, 2004). In the

1990s the average greenhouse tomato annual yield in the whole country was 28 kg/m² (Singgih, 1999). But now the situation has changed-the majority of New Zealand fresh market tomato growers produce their crops in hydroponic or semi-hydroponic systems; only a few of them still grow in soil (Vegfed, 2004). The average greenhouse size has increased. The largest growers now have up to 20 hectares in production under glass (Vegfed, 2004). As greenhouse growers have adopted more sophisticated technology and moved to more intensive systems, the tomato yield has also significantly increased. By 2005 the average greenhouse tomato annual yield was 45-50 kg/m² (HortNZ, 2006). However, although the greenhouse property sizes are increasing, the total number of greenhouse tomato growers has declined from 560 in 2002 to 375 in 2005 (HortNZ, 2006). The main reason is that growers with low-technology small-scale greenhouses can not drive their performance to enable them to survive without advanced technology, high investment, skilled management and sufficient profit (HortNZ, 2006).

As mentioned above, almost all the fresh market tomatoes in New Zealand are produced in greenhouse hydroponic growing systems. The advantage of a hydroponic growing system is that nutrients can be supplied in a more efficient and controlled manner (Jones, 2004). However, one of the characteristics of hydroponic growing is that from time to time surplus nutrient solution has to be discharged. When disease occurs or the salinity level is too high, or when the system needs to be cleaned between crops, a proportion of the nutrient solution is discharged to waste (Tuzel, Tuzel, Gul, Meric, Yavuz, & Eltez, 2001).

The surplus nutrient solution from a hydroponic system has a high concentration of nutrients, particularly nitrogen, phosphorus, and potassium (Hochmuth & Sweat, 1999). For large-scale greenhouses, the quantities of surplus nutrient solution can be huge (Martin, 2004). If disposal of the surplus nutrient solution is not carried out carefully it can have an adverse impact on the environment by polluting surface and groundwater (ARC, 2005c). Therefore, greenhouse nutrient solution management has been considered as one of the critical factors in greenhouse management.

Previously in New Zealand the emphasis on greenhouse tomato production was on increasing yields and improving fruit quality. But now sustainability and the environment have become important concerns for farmers and growers (PCE, 2004). The Resource Management Act 1991 (RMA) is an important piece of legislation that the government has developed to ensure the sustainability of the ecosystem. Regional councils set their local regulations and policies about resource management within the framework of the RMA. Some regional councils (e.g., the Auckland Regional Council) are concerned that many greenhouses are discharging nutrient solution to the environment in a way that is potentially harmful to the environment and inconsistent with sustainable management (ARC, 2005c). Therefore, management practices associated with reducing the environmental impacts of greenhouse nutrient solution release have recently been highlighted by regional authorities.

In order to assist the greenhouse growers to comply with the RMA and regional resource plans, *The Management of Nutrient Solutions Released from Greenhouses: A Code of Practice* (COP), which was funded by the Ministry of Agriculture and Forestry's Sustainable Farming Fund, Vegfed's Tomato Sector, Veg-Gro Supplies Ltd, Auckland Regional Council, Fertiliser Manufacturers' Research Association and Northern Flower Growers Association, has been developed and launched in 2006.

1.2 Problem Statement

In New Zealand, the tomato greenhouse industry has expanded rapidly during the past decade. In recent years the nutrient solution released from greenhouse operations has been considered as a potential pollution source by regional authorities. "*The Management of Nutrient Solutions Released from Greenhouses: A Code of Practice*" (COP) is designed to assist New Zealand greenhouse growers in managing the nutrient solution release in hydroponic systems to comply with the RMA and regional resource plans prepared by regional authorities to ensure that their constituents act appropriately. However, in New Zealand's greenhouse industry, production systems and greenhouse growers' level of

technical expertise vary. Little is known about the nutrient solution management and disposal practices of New Zealand hydroponic greenhouse tomato growers. Similarly, there is a paucity of information about the extent to which these growers follow guidelines provided in *The Management of Nutrient Solutions Released from Greenhouses: A Code of Practice* (COP).

1.3 Objective of the Study

The main objective of this research was to investigate the nutrient solution management and disposal practices of New Zealand hydroponic greenhouse tomato growers and, further, to investigate whether these practices meet the guidelines set out in *The Management of Nutrient Solutions Released from Greenhouses: A Code of Practice* (COP).

Specific objectives of the research are:

- 1). To obtain an in-depth understanding of the theory of nutrient solution management and disposal in hydroponic systems by reviewing the literature.

- 2). To investigate the nutrient solution management and disposal practices used by New Zealand hydroponic greenhouse tomato growers.

- 3). To compare the growers' nutrient solution management and disposal activities with the guidelines provided in the COP and the literature.

1.4 Thesis Structure

There are seven chapters in this thesis. Chapter One is the introduction. In this chapter the background of this research, including an overview of New Zealand's greenhouse tomato industry and the environmental concerns developing in relation to greenhouse nutrient

solution discharge, the research problem statement, and the research objectives, are outlined.

Chapter Two is the literature review. In this chapter, the theories of nutrient solution management and disposal in hydroponic systems and the guidelines for reducing impacts of the nutrient solution discharge on the environment are reviewed. Chapter Three is the research methodology. Chapter Four is the case study report. In this chapter, the details of the nutrient solution management and disposal activities used by the selected case studies are described. Chapter Five is the cross-case analysis. In this chapter, the results obtained in the case studies are compared with each other. Chapter Six is the discussion. In this chapter, the results from the cross-case analysis are compared to the general theories found in the literature and the guidelines given in the COP. Chapter Seven is the conclusion. The main findings from the research, the implications of the findings, an assessment of the research method, and future research suggestions are summarised in this chapter.

2. Literature Review

In this chapter, understanding of nutrient solution management in hydroponic growing systems is developed using material from the literature. The review starts with a central description of hydroponic growing systems; this is followed by a description of nutrient solution supply management, nutrient solution drainage management, and nutrient solution disposal for hydroponic systems. After that, the technical guidelines provided in the “*The Management of Nutrient Solutions Released from Greenhouses: A Code of Practice*” (COP) and regional council resources management plans are discussed. Lastly, a summary of the literature review is presented.

2.1 Hydroponic Growing Systems

In this section, the definition and classification of hydroponic growing systems, the characteristics of recirculating and run-to-waste hydroponic systems are described.

2.1.1 Definitions and Classifications

Hydroponics is the technique of growing crops without soil, either with or without media. All the water and nutrients the crops require are supplied in the nutrient solution (Mason, 1990; Hanger, 1993; Romer, 1993; Jones, 2004).

Hydroponic systems can be essentially classified into two groups in terms of the utilisation of growing media. One is the media system which uses growing media to support the plant roots and the other is the media-less system which does not use growing media to support the plant roots (Mason, 1990; Romer, 1993; Jones, 2004). Media hydroponic growing systems are ideal for long-term vegetables and flower crops (RIRDC, 2001). Common media include rockwool, vermiculite, perlite, sand, gravel, scoria, pumice,

expanded clay, expanded plastics, sponge foams, sawdust, and peat moss (Mason, 1990; Jones, 2004).

Hydroponic growing systems without growing media mainly include water culture, aeroponic, and nutrient film techniques (NFT) (Mason, 1990; Romer, 1993; Jones, 2004; Alto, 2006). Although some of these, such as NFT, are ideal for fruiting vegetables such as tomatoes, in commercial tomato production practice, generally media growing systems are preferred (RIRDC, 2001; Jones, 2004). Considering this research is focused on commercial growers, this literature review will be concentrated on the hydroponic growing media systems.

Hydroponic growing systems can also be classified in two ways in terms of the ways in which nutrient solution is supplied: one is an open or “run-to-waste” system and the other is a closed or “recirculating” system (Mason, 1990; Romer, 1993; Seymour, 1993; Donnan, 1994; Smith, 1999; Jones, 2004). In the run-to-waste systems, the nutrient solution is applied to the media in which the plants grow and then the excess is drained off as waste (Romer, 1993; Jones, 2004). In contrast, in the recirculating systems the excess nutrient solution is collected and recirculated (Romer, 1993; Jones, 2004).

Compared to recirculating systems, the advantages of run-to-waste systems are: relatively low investment and maintenance costs, low risk of root disease spreading, and the fact that it is easy to manage the supply nutrient solution composition (Romer, 1993; Saarinen, 1994; Savvas, 2002; Schnitzler, 2004). Research has shown that growing tomatoes in a run-to-waste system can more readily produce higher yields and better fruit quality despite the fact that use of water and fertiliser is inefficient (Giuffrida, Lipari, & Leonardi, 2003). However, in run-to-waste systems, large amounts of drainage lead to the emission of water and fertiliser, which not only increases the cost of production but also pollutes the environment. From an environmental point of view, the better situation is the use of recirculating systems because they physically obstruct any percolation of nutrients into the environment (Tognoni, Pardossi, & Serra, 1998; Schnitzler, 2004). Even in economic aspects, in a closed system, the nutrient solution consumption through the recirculating

system is lower than in a run to-waste-system (Garcia, Escobar, Salas, & Urrestarazu, 2000). Studies have shown that a recirculating growing system could save up to 30% of water and up to 40% of fertilisers, and reduce up to 65% of the potential nitrogen and phosphorus discharge to the environment compared to an open system (Magen, 1999; Van Os, 1999; Giuffrida et al., 2003; Bugbee, 2004; Dhakal, Salokhe, Tantau, & Max, 2005). Some researchers have indicated that although the initial investment in recirculating growing systems is high, their annual running costs are equal to, or lower than, those for run-to-waste systems (Van Os, 1994). Although some potential yield may be sacrificed by using recirculating systems, the environmental benefits mean that grower use of run-to-waste systems is declining (Van Os, 1994; Tognoni et al., 1998; Van Os, 1999; Giuffrida et al., 2003). Legislation in some countries, such as Netherlands and Canada, states that greenhouse growers can grow their products only in recirculating systems (Van Os & Benoit, 1999; MAFF, 2004a).

However, in a recirculating system, there is higher risk of root disease spreading compared to a run-to-waste system because the reused nutrient solution may carry pathogens from diseased plants throughout the whole system (Schnitzler, 2004). Furthermore, the reused nutrient solution may have a nutrient imbalance issue because the nutrients which comprise the solution are taken up by the plants at differing rates (Savvas, 2002). Therefore, nutrient solution management in recirculating systems is more complicated in comparison to run-to-waste systems, particularly in terms of salinity control (Savvas & Adamidis, 1999) and root disease control (Van Os & Postma, 2000).

To manage nutrient solution in hydroponic growing systems, it is necessary to understand the components involved in the system and how the nutrient solutions flow through the system. These details are presented in the following section.

2.1.2 System Design and Nutrient Solution Flow

The basic equipment in a hydroponic system includes tanks, pipes, pumps, salinity controllers, pH controllers, dripper systems, solenoid valves, time clocks, and computer control systems (Hanan, Holley, & Goldsberry, 1978; Mason, 1990; Magen, 1999; Smith, 1999). If the system is a recirculating one, it also includes disinfection equipment (Wohanka, 1995; Smith, 1999; Nederhoff, 2000a, 2000b, 2000c). In different greenhouse management guidebooks, the descriptions of the uses of this equipment are expressed in many ways. However, they can be summarised as:

- Sump and storage tanks are used for mixing and storing the supplied and run-off nutrient solution.
- Pumps are used for moving nutrient solution through the system.
- A salinity controller monitors and shows the electrical conductivity (EC) level in the solution at all times, and operates injection pumps which add concentrated nutrient solution to the solution in the system when the EC level falls, or add fresh water when the EC level rises.
- A pH controller is a device linked to an electrode in the catchment tank. It can be programmed to inject predetermined amounts of acid or alkaline solution into the catchment tank if the pH reaches an upper or lower limit.
- A solenoid valve is installed to operate as a tap connecting a tank holding nutrient solution into the irrigation line.
- Time clocks can provide a simple means of automatically controlling multiple operations such as turning water supplies on and off, and adding nutrients.
- Computer systems, which are more commonly used in modern greenhouses and industries, can undertake tasks from controlling, monitoring and recording information relating to environmental conditions in the growing area, to arranging the volume and timing of nutrient solution applications, and the management of pH and EC of both the input and run-off solution.
- Filter systems can remove dust, some pathogens and bacteria from the irrigation water and nutrient solution.

- Disinfection systems such as UV units, Ozonation units, and heating system kill the pathogens and bacteria in the irrigation water and nutrient solution.

Source: (Hanan et al., 1978; Mason, 1990; Magen, 1999; Smith, 1999)

The nutrient solution flow in a typical recirculating hydroponic system is illustrated in Figure 2.1.

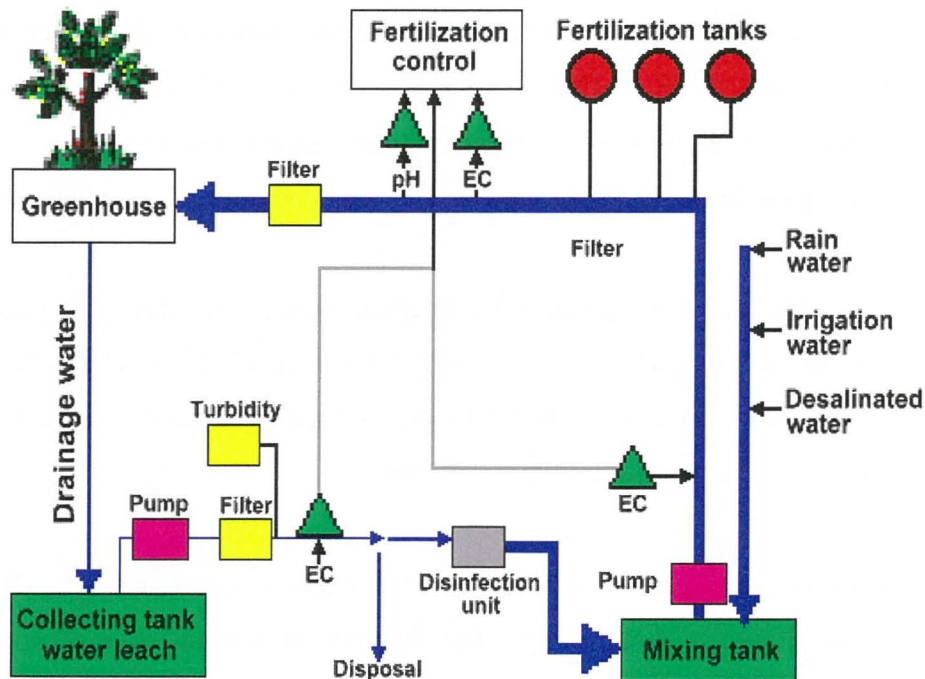


Figure 2. 1 Nutrient solution flow in a recirculating hydroponic system. Source: (Magen, 1999)

In a recirculating system at the beginning of the nutrient solution supply, fresh water from various resources (which may include rain water, town supply water, bore water, etc.) and the reused nutrient solution from the greenhouse are combined in the mixing tank. After the fresh water and reused nutrient solution are blended, the mixture is pumped out from the mixing tank to blend with fresh nutrient solution after EC adjustment.

To avoid the precipitation of calcium and most of the phosphate as insoluble calcium phosphate, fresh nutrient solutions usually are split into two parts as “Solution A” and “Solution B” and are stored in different storage tanks before they are blended and supplied to the greenhouse crops (Mason, 1990; Donnan, 1994; Smith, 1999; Jones, 2004). Solution A usually contains calcium nitrate and iron chelate and Solution B contains all the other fertilisers (Mason, 1990; Donnan, 1994; Smith, 1999; Jones, 2004).

The mixed nutrient solution then goes through a filter to be applied to the plants after EC and pH adjustment. The excess nutrient solution from the greenhouse can be collected then stored in the collecting tank. The nutrient solution in the collecting tank will be pumped out of the tank for sterilising through the disinfection units to flow to the mixing tank again for reuse. If solution is not able to be reused, it can be disposed of at this stage.

In a run-to-waste system, the nutrient supply process is similar to that used in a recirculating system but the drained nutrient solutions from the greenhouses are not recirculated. They are either disposed of directly from the bottom of the plants, or after being collected and stored (Smith, 1999).

In summary, the entire nutrient solution management process in a hydroponic system can be described in three phases. The first one is nutrient solution supply management; the second one is nutrient solution drainage management (for a recirculating growing system), including drainage collection and reuse; and the last one is nutrient solution disposal. Management details in each phase are discussed in the following sections.

2.2 Nutrient Solution Supply Management

In this section, the literature regarding nutrient solution supply management is reviewed. In section 2.2.1 characteristics of nutrient solution supply in hydroponic media systems are discussed. In section 2.2.2 key factors which affect nutrient solution drainage are presented.

2.2.1 Characteristics of Nutrient Solution Supply in Hydroponic Media Systems

The first step of a nutrient solution supply is to formulate the nutrient solution. Three key factors should be considered in nutrient solution formulation: they are the solution's composition, pH¹, and electrical conductivity (EC)² (Mason, 1990; Romer, 1993; Donnan, 1994; White, 1997; Wilkerson, 1998; Jones, 2004; Peet, 2004b).

Nutrients can be classified as *major* or *minor nutrients* and both are necessary for crop growth. *Major nutrients* are needed in significant quantities by plants. They include *nitrogen, phosphorus, potassium, magnesium, calcium, and sulphur*. *Minor nutrients*, although needed in only small amounts, are also necessary. They include *iron, copper, boron, manganese, zinc, cobalt, and molybdenum* (Mason, 1990; Romer, 1993; Donnan, 1994; White, 1997; Wilkerson, 1998; Jones, 2004; Peet, 2004b). Many different nutrient solution recipes can be used in hydroponic tomato growing. Although the recipes can be different, the nutrient solution pH and EC should be maintained at certain target levels for each (Mason, 1990; Romer, 1993; Donnan, 1994; White, 1997; Wilkerson, 1998; Jones, 2004; Peet, 2004b). The pH of the solution affects the form and availability of nutrients in the irrigation water. For New Zealand greenhouse tomato growing, the recommended

¹ The pH is measured on a logarithmic scale ranging from 0 to 14 with 7 being considered neutral, above 7 being considered alkaline and below 7 as acid (Mason, 1990).

² Electrical conductivity (EC) is a measure of the rate at which a small electric current flows through a solution. It is expressed as milliohms per centimetre (mMho/cm) or as millisiemen per centimetre (mS/cm) (Mason, 1990).

suitable range for pH is 5.0~6.3 because these levels enhance the solubility of most nutrients (White, 1997). The EC is an important measure of the total solute concentration (salinity level) of the nutrient solution in the root environment. It mainly influences plant function through its effect on plant water relation (Peet, 2004a). If the EC in the root environment is too high, the availability of water to the roots of the plant could be reduced, and water uptake and plant growth rate will be decreased (Peet, 2004a). If the EC is too low, the tomato plants will not be able to obtain sufficient nutrients (Peet, 2004b). The optimum nutrient solution EC recommended by White (1997) for New Zealand greenhouse tomato growing is between 2.0 mS/cm-8.0 mS/cm.

While nutrient solutions are supplied to the growing media, tomato plants take up not only part of the nutrient elements in the solution, but also a larger amount of water because of the need for transpiration (Mason, 1990; Jones, 2004; Peet, 2004b). Also, the water in the growing media will be lost due to evaporation (Nichols, 1989; Mason, 1990). Therefore, some unusable parts of the nutrient remain in the root zone and lead to salt residues. As the EC of the nutrient solution rises there is increased risk of salinity issues (Mason, 1990). When residual salt level in the media becomes too high, water uptake declines and overall growth rate drops (White, 1997; Peet, 2004b), also crop roots are damaged (Voogt & Sonneveld-van Buchem, 1988). The salt build up problem can be solved by supplying a greater volume of nutrient solution than the crop requires to flush the growing media (Fabre & Jeannequin, 1995; Adams, 1999; Garcia et al., 2000; Savvas, 2002; Bar-Yosef, Fishman, & Klaring, 2004). Therefore, allowing drainage to occur to avoid the harmful salt build up in the root zone is considered as one of the key strategies used in nutrient solution supply management for hydroponic media growing systems.

The literature is not clear about the optimum drainage percentage for tomato growing in media systems. Some researchers have reported that in media growing systems, having a high percentage of nutrient solution drainage has a significant positive influence on tomato yield, as well as fruit quality (Fricke, 1998; Tuzel, Tuzel, Gul, Altunlu, & Eltez, 2001). However, researchers also claim that too high a percentage of nutrient solution drainage increases the fertiliser and water consumption, and hence increases the

production costs. Even in recirculating systems, where the drained nutrient solution can be collected and reused, a large drainage volume increases the disinfection costs (Fricke, 1998; Sonneveld & Voogt, 2001). Therefore, in either run-to-waste systems or recirculating systems, nutrient solution drainage control is considered a critical part of nutrient solution management. In order to save water and fertiliser and also avoid salt stress in the root zone, some researchers have suggested using the supply of low volumes of low EC nutrient solution as an alternative method. This strategy particularly suits run-to-waste systems (Giuffrida & Lipari, 2003). The normal percentage of nutrient solution drainage suggested in the literature is 25%-40% of the supplied volume (Mason, 1990; Romer, 1993; Wilkerson, 1998; Jones, 2004). However, the actual drained volume varies under different conditions. Factors affecting the nutrient solution drainage will be discussed in the following section.

2.2.2 Key Factors Which Affect Nutrient Solution Drainage

As nutrient solution drainage is a strategy used to prevent salt build up in the root zone, the nutrient solution drainage volume is largely determined by the root zone salinity level, which is measured by EC (Mason, 1990; Romer, 1993; Donnan, 1994; White, 1997; Wilkerson, 1998; Jones, 2004; Peet, 2004b). Therefore, factors which affect the root zone salinity level are considered important in the drive to reduce the drainage volume. These factors are irrigation water quality, growing media type, air temperature, solar radiation, and crop growing stage.

2.2.2.1 Irrigation Water

The literature provides various definitions of water quality. Donnan (1994) and Wilkerson (1998) pointed out that in terms of nutrient solutions management, the most important factor in irrigation water quality is its salts content (ions).

Irrigation water may contain varieties of ions such as sodium, chloride, Calcium, and Magnesium and so on (Donnan, 1994; Wilkerson, 1998; Jones, 2004). Among these, sodium and chloride are not taken up to any degree by most plants. Hence they tend to accumulate in the nutrient solution (Donnan, 1994; Jensen, 1997; Magen, 1999; Jones, 2004). In recirculating growing systems, when the unwanted salt concentration in the solution is beyond a certain limit, the system becomes unmanageable. In this situation, the nutrient solution is not reusable and has to be replaced (Donnan, 1994; Magen, 1999; Jones, 2004). Therefore, using irrigation water with low concentrations of sodium and chloride to formulate the nutrient solution helps to prolong the nutrient solution's life in recirculating growing systems (Donnan, 1994; Magen, 1999; Giuffrida et al., 2003).

Calcium and magnesium are nutrients that tomato plants require and therefore their presence in the irrigation water is allowed for in calculating formulations (Donnan, 1994). However, they readily accumulate in the root zone and lead to salinity issues because they may not be absorbed readily by plants (Jones, 2004). Therefore only when their concentration in the irrigation water is within a certain range (calcium 40-100 ppm, magnesium 30-50 ppm) is the irrigation water quality considered acceptable (Will, 2003). Calcium and magnesium concentrations are also indicators of the water hardness³ (Donnan, 1994; Will, 2003). As hard water contains a high concentration of calcium carbonate, when hard water is used to formulate nutrient solution, usually it is not necessary to add additional calcium and/or magnesium otherwise it easily leads to a salinity issue. In contrast, if soft water is used to formulate nutrient solution, it is necessary to add further calcium and/or magnesium otherwise it will not be able to match the crops' nutrient requirements (Will, 2003). In recirculating hydroponic systems, water and nutrient solution disinfection is necessary (Smith, 1999; Nederhoff, 2000c; Jones, 2004). Heat treatment is one of the most powerful sterilisation methods for pathogen control (Nederhoff, 2000c). However, if source water contains large amounts of calcium, the heating treatment will precipitate calcium deposits in the form of scale on the heat

³ If the irrigation water has an alkalinity in excess of 100mg/l calcium carbonate equivalent, then the water is defined as "hard" (Will, 2003). If the water sample has an alkalinity of less than 100mg/l calcium carbonate equivalent, the water is defined as "soft" (Will, 2003).

exchangers. In this situation, the temperature of the heat treatment should be increased (Nederhoff, 2000c).

When irrigation water contains too high a concentration of ions, it has to be treated to remove the bulk of the salts from the water, typically with reverse osmosis, before it can be used for hydroponics (Donnan, 1994). In practice, rainwater collected from greenhouse roofs is an ideal irrigation water source because rainwater has fewer salinity problems compared to water from other sources (Mason, 1990; Runia, 1995; Johnson, Salter, Smith, & Hall, 1999; Magen, 1999; Schwarz, Grosch, & Gross, 2004).

Besides ion concentration, Jones (2004) indicated that other inorganic and organic components in the water should be considered in nutrient solution management. In recirculating systems, when serious root pathogens have been found, the nutrient solution has to be totally replaced. Therefore the cleanliness of irrigation water must be considered because it will directly affect the probability of root disease occurring hence it is necessary to replace the nutrient solution frequently (Jones, 2004; Schwarz et al., 2004). Using surface water as an irrigation water source is a risk because it may contain disease organisms and algae (Jones, 2004). Irrigation water, which has been taken from a river, shallow well, or even rainwater collected from a greenhouse roof, may contain both inorganic and organic substances that can affect plant growth. Water from these sources should be tested before it is used. If it is necessary the water will need to be treated (Jones, 2004). Common water treatment methods to remove pathogens and algae includes Ultra-violet (UV) treatment, slow sand filter, ozonation, and heat treatment (Wohanka, 1995; Nederhoff, 2000a, 2000b, 2000c; Schwarz et al., 2004).

2.2.2.2 Growing Media

In media growing systems, the growing media's water holding capacity is one of the key factors influencing irrigation management (Tuzel et al., 2001). Water holding capacity influences the oxygen levels in the root zone, which affects nutrient uptake and crop yield

(Adams, 1999). If the growing media cannot drain freely, because they have a too high water holding capacity, then the root zone oxygen level may be low. Too low an oxygen level in the root zone reduces nutrient uptake (Adams, 1999). Therefore the irrigation schedule should be different for different types of growing media (Mason, 1990; Romer, 1993). When growing tomatoes in a high water holding capacity medium, to avoid low oxygen levels in the root zone, irrigation should be supplied less frequently but at a larger volume per time. In contrast, if the growing medium has low water holding capacity, the water supplied to the crops can quickly be lost and the medium will dry out easily (Adams, 1999). Therefore, when using low water holding capacity growing media, to avoid water shortage in the root zone the irrigation frequency should be increased and the supply volume per time should be reduced to avoid excess run off (Mason, 1990; Romer, 1993; Gunnlaugsson & Adalsteinsson, 1995; Adams, 1999). For example, research has shown that although the yields of tomatoes grown in pumice and rockwool are similar, irrigation for pumice has to be adjusted to give frequent watering with a small volume each time because pumice has lower water capacity than rockwool (Gunnlaugsson & Adalsteinsson, 1995; Austin, 2006). In terms of nutrient solution drainage volume, for tomato crops grown in rockwool the general drainage percentage is approximately 30% to 40% of plant solution⁴. However, for tomato crops grown in pumice, the drainage percentage should be between 40% and 100% of plant solution (Lewthwaite et al., 2006). However, different growing media have their advantages and disadvantages. For example, rockwool has good water holding capacity and it is chemically and biologically inert (Bussell, 2004). It is free of any potential pests, diseases, and weed seed because it is manufactured in high temperatures. Therefore, it is one of the most popular growing media in greenhouse production (Bussell, 2004). Another popular growing medium is pumice, because although it has low water holding capacity and requires more careful irrigation management, it is cheap (Gunnlaugsson & Adalsteinsson, 1995). Also, pumice can easily be sterilised with steam or other sterilising agents and be reused. Therefore, pumice is considered as an environmentally friendly and economic alternative growing medium (Gunnlaugsson & Adalsteinsson, 1995).

⁴ Plant solution means the water and nutrients in the solution are used by the plant for structural growth, evapotranspiration and crop production (Lewthwaite, Cornforth, Bussell, Ivicovich, Smellie, Smith, & Robertson, 2006).

2.2.2.3 Temperature and Solar Radiation

In greenhouses, air temperature and solar radiation are both considered significant factors in irrigation management (Nichols, 1989; Valente, Boaventura Cunha, & Couto, 1998; Peet, 2004b). This is because when air temperature and solar radiation levels are high, plants need more water to meet the atmospheric demand, therefore the water consumption increases (Nichols, 1978; Fereres, 1997; Valente et al., 1998). In order to meet the plants' requirement, the irrigation volume should be increased. However, although the plants require more water when the air temperature and solar radiation are high, their nutrient requirements may not be more than their usual amounts (Jones, 2004). Therefore, the unusable nutrient elements in the supplied nutrient solution will remain in the root zone and the nutrient solution drainage. As a result, salinity issues are more likely to occur in the growing media when temperature and solar radiation are high (Jones, 2004; Peet, 2004b). In order to meet the plants' water requirement and to avoid salt build up, there is a need to supply more irrigation volume and to allow more drainage volume to flush the growing media in this condition. At the same time the concentration of the supply nutrient solution should be reduced to avoid salt accumulation (Donnan, 1994; Valente et al., 1998; Peet, 2004b).

As air temperature and solar radiation vary depending on the season, nutrient solution management also varies with the season. In New Zealand, temperature and light level are generally high during summer and low in winter (NIWA, 2004). Therefore, tomato plants' water consumption is high in summer⁵ and low in winter⁶. As salinity issues are more likely to occur during summers, higher volumes of drainage are required to solve the problem.

Solar radiation also changes during a day, therefore the daily irrigation schedule in greenhouses is usually determined by solar radiation, air temperature, and humidity

⁵ In New Zealand summer means weeks 40 to 17 of the year (Lewthwaite et al., 2006).

⁶ In New Zealand winter means weeks 22 to 35 of the year (Lewthwaite et al., 2006).

monitoring results (Nichols, 1989). During the daytime, when solar radiation is high, the plants require more water so the irrigation supply and drainage volume should be greater than they are during the night. During night time, as there is no solar radiation, normally an irrigation supply is not required (Nichols, 1989).

2.2.2.4 Crop Growing Stage

As the crop develops its nutrient and water requirements differ. Before transplanting, the tomato plants are normally grown in propagators containing the sown cubes or pots. At this stage, plants require limited water and are normally just irrigated several times daily to keep the root zone moist (Wilkerson, 1998; Peet, 2004a). After transplanting, especially when the plants develop and start flowering and setting fruit, they require more water and nutrition. When tomato crops begin to set fruit, nutrient solution management becomes extremely significant in terms of supply volume, as well as its composition (Wilkerson, 1998; Peet, 2004a). If the tomato crops suffer water stress at their fruit setting stage, they will not be able to obtain sufficient nutrients and therefore they will not produce high yields and good fruit quality (Peet, 2004b). Generally the water and nutrition supply should be increased to the maximum volume by peak fruit ripening (White, 1989, 1997).

Several authors have reported that improving tomato fruit quality during the peak harvest period can be achieved by increasing nutrient solution concentration (Anon, 2000; Dorais, Dorval, Demers, Micevic, Turcotte, Hao, Papadopoulos, Ehret, & Gosselin, 2000; Hao, Papadopoulos, Dorais, Ehret, Turcotte, & Gosselin, 2000; Okano, Sakamoto, & Watanabe, 2000; Li, Stanghellini, & Challa, 2001; Peet, 2004a). Therefore, during this growing phase, the supply nutrient solution EC can be increased and the root zone EC maintained at the higher end of the recommended ranges. As a result, less drainage is required to flush the growing media to reduce the root zone EC in this growing phase than in earlier, vegetative, phases.

2.3 Nutrient Solution Drainage Management

Since supplying increased volumes of nutrient solution to crops to allow drainage to occur is one of the characteristics of media hydroponic growing, managing nutrient solution drainage is a significant part of the process of nutrient solution management, which will be discussed in this section.

2.3.1 Collection and Storage

In some of the run-to-waste systems, there are no nutrient solution drainage collection and storage facilities, the nutrient solution drainage from the media containers passes directly to the soil and thus to the groundwater. These systems are classified as “open drainage systems” by Tognoni, Pardossi, and Serra (1998). In other run-to-waste systems, although the nutrient solution drainage is not for reuse, it is collected through pipes and stored before disposal and therefore these systems are classified as “guided drainage systems” (Tognoni et al., 1998). In recirculating systems, the nutrient solution drainage is collected and stored before it is recycled (Tognoni et al., 1998; Smith, 1999). The ways to collect the nutrient solution drainage include flume, collection pipe, gravel surface and subsurface drain, and sculpted concrete floors (Mason, 1990). In “guide drainage systems” and recirculating systems, the nutrient solution drainage is stored after being collected.

The basic principle of drainage storage capacity design in a hydroponic system is to prevent any pollution due to overflow, but includes a 10% buffer capacity (Bell & Marchant, 1998). The storage capacity is determined by drainage volume and the storage period (Smith, 1999). In some recirculating systems, the drainage nutrient solution is used for continuous recycling and therefore it is stored in the storage facilities for a short period only (Smith, 1999). In these systems generally it is not necessary for designing too large a drainage nutrient solution storage capacity. However, in some recirculating systems, the nutrient solution drainage is supplied to the tomato crops from the final stage of ripening to the end of the crop cycle only (Okano et al., 2000). The advantages of this drainage

management strategy are, on the one hand, that it utilises the high EC nutrient solution drainage to improve the tomato fruit quality during the peak harvest period, and on the other hand, it ensures that no drainage remains from the previous crop cycle (Okano et al., 2000). As in these systems the nutrient solution drainage needs to be stored for a longer period, the required storage capacity is bigger than in continuously recirculating systems.

2.3.2 Factors Which Affect the Nutrient Solution Reuse Cycle

In recirculating systems, nutrient solution management is more complicated than it is in run-to-waste systems because the nutrient supplied to the crops depends not only on the composition of stock fresh nutrient solution but also on the composition of the reused nutrient solution (Bell & Marchant, 1998; Magen, 1999). Salinity build-up and root pathogens are the two key factors that directly affect the nutrient solution reuse cycle (Magen, 1999).

When fresh nutrient solutions are supplied to the plants, each nutrient in the solution is taken up by plants at a differing uptake rate (Sonneveld & Voogt, 1980; Sonneveld, Bos, & Voogt, 2004). As a result, the nutrients which plants absorb at high uptake rates, such as nitrogen and phosphorus, tend to be deficient in the drainage. In contrast, the nutrients which plants absorb at low uptake rates, such as calcium, magnesium and sulphur, or elements which are never absorbed by plants, such as sodium and chloride, tend to be accumulated in the drainage (Donnan, 1994; Jones, 2004). The more cycles for which the drained solution is re-used, the higher the concentration of accumulated salts in the solution. When the concentration of unwanted elements in the reused nutrient solution accumulate to too high a level, the drainage nutrient solution can not be reused and has to be expelled from the system (Donnan, 1994; Stanghellini, 1997). Therefore, the drainage nutrient solution's salinity level, which is measured by EC, is considered as one of the key factors affecting its reuse cycle (Donnan, 1994; Bell & Marchant, 1998; Magen, 1999; Savvas & Adamidis, 1999; Kempkes & Stanghellini, 2003). Irrigation water quality can

significantly affect the nutrient solution reuse cycle, particularly its sodium, chloride, and calcium concentration. Details have been discussed in 2.2.2.1 *Water quality*.

In recirculating systems, the drainage nutrient solution may carry out root disease pathogens and spread them to the whole system. Once a serious root pathogen has been identified, the nutrient solution can not be reused and has to be replaced (Van Os, 1999). Therefore, root pathogen control is another factor which affects nutrient solution reuse (Van Os, 1999). Further, as growers do not know when serious infection will take place, nutrient solution disposal in these circumstances is a “forced action”. Release must occur to stop disease spread. Therefore, root disease control becomes significant and necessary in recirculating systems (Van Os, 1999; Schnitzler, 2004).

There are a number of technologies available to reduce root disease risk, including the use of pathogen-free growing media, clean irrigation water, and biological/chemical control (Van Os, Runia, & Buuren, 1998; Van Os & Postma, 2000; Schnitzler, 2004; Schwarz et al., 2004). Schnitzler (2004) stated that when the growing media are used for one crop cycle only, the root disease risk is low. When the growing media need to be reused, they must be disinfected. Also, root disease is more likely to occur in high temperature, wet, and acidic conditions. Therefore, to optimise growing factors such as temperature, water, pH and nutrient according to the plants’ need to reduce stress is considered significant (Schnitzler, 2004).

As the salinity level and root disease pathogen content are the two key factors affecting the nutrient solution reuse cycle, irrigation water and nutrient solution treatment is considered as a special technical activity in nutrient solution drainage management in hydroponic recirculating growing systems (Van Os & Postma, 2000; Schnitzler, 2004).

2.3.3 Irrigation Water and Nutrient Solution Treatment

Nutrient solution treatment for recirculating growing systems is focused mainly on disinfection (Van Os, 1999). In terms of root pathogen control, sterilising methods include ozonation, filtration, Ultra-violet (UV) sterilisation, and heat treatment (Runia, 1995; Schnitzler, 2004).

Ozone gas (O_3) is a powerful oxidant which kills bacteria, fungi and viruses in raw water or nutrient solution without leaving a residue (Smith, 1999). It not only precipitates any organic matter out of the water but also adds oxygen to water, which is good for plant growth (Smith, 1999; Evans, 2003; Lewthwaite et al., 2006). Therefore ozonation is considered a clean and safe sterilising method which produces no harmful by-products (Smith, 1999; Evans, 2003). However, some researchers claim that ozone flocculates soluble iron and manganese in water, possibly causing water to be unsuitable for recirculating systems (Smith, 1999). As the nutrient solution drainage generally contains iron and manganese, ozonation is not preferred for recirculating solution treatment, but is more appropriate in the source water treatment (Smith, 1999; Lewthwaite et al., 2006).

Filtration with filters can remove some pathogens and other suspended material in the water (Fox, 1995). The filter material can be sand, lava, or rockwool (Fox, 1995). However, filtration can not remove viruses or all pathogens (Fox, 1995; Smith, 1999; Van Os, 1999; Lewthwaite et al., 2006). Therefore, in practice filtration is better used in conjunction with Ultra-violet for the removal of viruses (Fox, 1995; Runia, 1995).

Ultra-violet radiation is safe and convenient and therefore it is considered as the most common disinfection method in modern greenhouses (Romer, 1993; Smith, 1999; Nederhoff, 2000a; Lewthwaite et al., 2006). A dose of UV radiation can kill pathogens in water and hence prevent the spread of disease (Nederhoff, 2000a). Although it is expensive, it is considered more economic than most other methods because of its efficiency. Therefore it is often used to sterilise greenhouse drainage before reuse (Nederhoff, 2000b). However, as the UV dose received by the pathogens in the water

depends on physical factors, the water needs to be as clear as possible. Therefore in practice, before UV treatment is applied to drainage, the drainage generally should be filtered (Nederhoff, 2000a).

Another powerful method for controlling pathogens in water or in drained nutrient solution is heat treatment (Nederhoff, 2000c). This method can control all pathogens in raw water or drainage nutrient solution (Nederhoff, 2000c; Lewthwaite et al., 2006). However, when source water contains large amounts of calcium, bicarbonate and other compounds, heating will cause calcium to precipitate and form scale on the heat exchangers (Nederhoff, 2000c; Lewthwaite et al., 2006). This problem can be solved by lowering the pH of the water or solution before it enters the treatment unit (Nederhoff, 2000c).

When source water or reused nutrient solution contains too high concentrations of unwanted ions, removing the bulk of salts from the irrigation water and solution is considered necessary. In practice, reverse osmosis using membrane technology is the most useful method for removing the bulk of salts from the water and solution (Donnan, 1994).

2.4 Nutrient Solution Disposal

When nutrient solution drainage can not be reused, it should be released out of the system. The nutrient solutions have high nutrient contents and low organic carbon concentrations. Therefore, the release of solution can result in adverse environmental effects, especially the increased nitrate concentrations in groundwater and nutrient enrichment of surface water (Tognoni et al., 1998; Prystay & Lo, 2001; Lewthwaite et al., 2006). In this section, the literature regarding nutrient solution disposal is reviewed. Firstly the nutrient solution release environmental impacts are discussed, followed by the strategic practices for reducing nutrient solution's environmental impacts. Lastly, policies and guidelines regarding sustainable farming and greenhouse nutrient solution disposal in New Zealand are reviewed.

2.4.1 Nutrient Solution Release and its Major Environmental Impacts

2.4.1.1 Nitrogen in Nutrient Solution

Nitrogen is essential to many functions within the plant and is a primary constituent of the basic amino acids which are the building blocks of protein (McLaren & Cameron, 1996). Some researchers have indicated that nitrogen probably has a greater total influence on plant growth than most of the other elements because nitrogen level markedly affects plant growth, fruit yield and quality (Adams & Massey, 1984; Jones, 2004). Plant requirements for nitrogen are sometimes larger than those for all of the other elements combined (Bugbee, 2004). The literature has shown that the total amount of nitrogen taken up during one tomato growing season (seven months) can be up to 302 kg/ha (Schroder, Schwarz, & Kuchenbuch, 1995). Therefore, nitrogen is considered to be one of the essential elements when formulating nutrient solution (Mason, 1990; Romer, 1993; Schwarz, 1995; Jones, 2004). Jones (2004) recommends that the average nitrogen concentration in the nutrient solution for tomato growing should be 171ppm. However, at different growth stages, nitrogen concentration in the nutrient solution can be changed. Table 2.1 shows a sample of the general guidelines for the amount of nitrogen to use.

Table 2. 1 Amount of nitrogen to use in different tomato growing stages. Source: (Snyder, 2000)

Stage of growth	Nitrogen (ppm)
Germination to first true leaf fully expanded	50
First true leaf to third true leaf fully expanded	50-75
Third leaf to transplant	75-100
Transplant to second cluster set	100-125
Second cluster to topping	125-200

Nitrogen can be taken up by the plant either as nitrate (NO_3^-) or as ammonium (NH_4^+) ions from nutrient solution (Schwarz, 1995; McLaren & Cameron, 1996; Jones, 2004). Some reports from the literature have claimed that ammonium can be toxic to plants and results in slowed growth and development. If the ammonium ions are the major nitrogen source in the nutrient solution, tomato plant growth can be significantly reduced at high light conditions (Donnan, 1994; Jones, 2004). Therefore, ammonium percentage in the nutrient solution should not exceed 50% of the total nitrogen concentration and the best ratio recommended by Jones (2004) is 75% nitrate to 25% ammonium.

When greenhouse nutrient solution is supplied to the crops, nitrogen in the nutrient solution can be absorbed by the plants or discharged out of the system with the nutrient solution drainage. As nitrogen concentration in nutrient solution is generally higher than all of the other nutrients and is mainly in nitrate form, it is considered to be the most significant (and most frequent) kind of contaminant from greenhouse nutrient solution release (MFE, 1997; Lewthwaite et al., 2006).

2.4.1.2 Nitrogen and Ground Water

Since nitrate is both mobile and unstable, when it moves downwards through the soil it eventually:

1. *reaches the ground water;*
2. *or, moves into land-drains and then discharge to streams and enriches rivers or lakes;*
3. *enriches ground water and surface water, (McLaren & Cameron, 1996)-all of which are undesirable*

Water quality is one of the indicators of environmental health (MFE, 1997). One of the major water quality conditions of concern in New Zealand is elevated nitrogen and phosphorus levels (Anon, 2000; MAF, 2000; Hudson & Harding, 2004). High levels of nitrate can pose a health risk for people, hence, the *Drinking Water Standards for New*

Zealand set a maximum acceptable level (MAL) of 11.3mg/L for nitrate-nitrogen (CDHB, 2005). High levels of nitrate in drinking water can also affect livestock (Selvarajah, Maggs, Crush, & Ledgard, 1994). Moreover, when nitrate leaches through soil, it removes some nutrients such as calcium, magnesium and potassium, which acidifies the soil (Manahan, 2004; Lewthwaite et al., 2006).

2.4.1.3 Contaminants in Nutrient Solution

Although nitrogen may be present in greenhouse nutrient solution drainage in three forms, which are urea, ammonium (NH_4^+), or nitrate (NO_3^-), the nitrate form is the highest concentration (Jones, 2004). Further, the urea and ammonium forms are transformed into the nitrate form when the nutrient solution is applied to the soil (McLaren & Cameron, 1996; Lewthwaite et al., 2006). Therefore, the most significant and most frequent kind of groundwater pollution from greenhouse nutrient solutions is the accumulation of nitrate-nitrogen (MFE, 1997; Lewthwaite et al., 2006).

Phosphorus is another significant nutrient content in nutrient solution drainage (MFE, 1997). Although phosphorus is far less susceptible to leaching to the environment than nitrogen, it is readily mobilised by soil erosion (PCE, 2004). Hence, phosphorus also affects the environment through run-off and to a lesser extent through leaching. However, in greenhouse nutrient solution drainage management, it could be assumed that when the nitrogen content in the solution is managed, the phosphorus will also be managed (Lewthwaite et al., 2006). Therefore, concerns about greenhouse nutrient solution disposal are focused on how to reduce environmental damage from the nitrogen and phosphorus in New Zealand (MAF, 1992, 2000; MAFF, 2004b).

2.4.2 Strategies and Practices Used to Reduce Nutrient Solution Release Environmental Impacts

In this section, literature regarding greenhouse nutrient solution disposal is reviewed. In section 2.4.2.1, nutrient solution release options are discussed. In section 2.4.2.2 nutrient solution release site and release condition are discussed.

2.4.2.1 Nutrient Solution Release Options

Like other agricultural effluent, greenhouse nutrient solution drainage is most likely to affect the ground water and surface water quality. Therefore, applying released solution to land, rather than discharging it directly into water, can help reduce the impacts of greenhouse production on water quality (MFE, 1997; MAF, 2000).

Nitrate leaching is possible only when water drains through soil pores or through cracks in dry soils (Cornforth, 1998). If the selected release site has slow drainage or slow water infiltration rates, the water will run off the soil surface easily which will lead to increasing erosion and the transferring of nutrient to surface waters (Cornforth, 1998). For this reason, a suitable nutrient solution release site should have a good soil drainage ability and infiltration rate (Cornforth, 1998).

Many outdoor crops require large amount of nitrogen for their growth. For example, in cauliflower growing the nitrogen requirement is 150-250 kg/ha, for winter cabbage it is 350 kg/ha, for brussels sprouts it is 290 kg/ha, for early potato it is 350 kg/ha, and for winter spinach it is 350 kg/ha. Leafy vegetables, such as spinach, require 17 kgN/ha daily during the peak harvest period (Wood, 1995). As the released nutrient solution contains a large amount of nutrients, the literature shows that the best option for its disposal is to reuse it as a fertiliser to irrigate crops such as these (Bell & Marchant, 1998; RIRDC, 2001).

If the released nutrient solution is not used as fertiliser to apply to crops, it is considered as a waste liquid (Bell & Marchant, 1998). In this case one of the options for nutrient solution disposal is its release into a sewerage system (Bell & Marchant, 1998).

2.4.2.2 Nutrient Solution Release Site and Release Condition

Nitrate is mobile and unstable in highly moist soils (McLaren & Cameron, 1996). When selecting a nutrient solution release site, to avoid the nitrate and other nutrient element runoff and leaching, the soil moisture content needs to be considered. Nutrient solution should never be supplied to a site with high soil moisture (Cornforth, 1998; NZFMRA, 2002).

When nutrient solutions are used as fertilisers for secondary purposes to irrigate outdoor crops or pastures, the nitrogen should be used or disposed of in a way that prevents, avoids, minimises, remedies or mitigates leaching and runoff (Cornforth, 1998; NZFMRA, 2002). The timing of fertiliser application should be such that plant uptake is maximised so that any potential adverse environmental effects from biologically available nutrients are minimised (NZFMRA, 2002).

In addition to nutrient solution release site selection, the application methods for released solutions are important. Common methods include release with sprinklers, drippers, flood, and others. Sprinklers are the preferred application method because they provide more control over the time the water is applied and the amount of water supplied than do other methods (McLaren & Cameron, 1996).

In New Zealand, soil moisture deficits are related to seasons (McLaren & Cameron, 1996; Cornforth, 1998). During summer, when rainfall is low, the evapotranspiration is high so the soil moisture deficit is high (McLaren & Cameron, 1996; NIWA, 2004). Hence, when releasing nutrient solutions to land in summer, the nitrate leaching risk is low. In contrast, during winter-when rainfall is high-the evapotranspiration is low so the soil moisture

deficit is low (McLaren & Cameron, 1996). Hence, when releasing the nutrient solutions to land in winter, the nitrate leaching risk is considered high (McLaren & Cameron, 1996; NIWA, 2004). In most areas of New Zealand, nitrate leaching mainly occurs in late autumn, winter and early spring (McLaren & Cameron, 1996; NIWA, 2004). Therefore, the possibility of releasing nutrient solution to land during these periods without nitrogen leaching is low.

If the site is one of the areas shown below, it is said to be a sensitive area unsuitable for nutrient solution release. These areas are not the best for release sites because nutrient can readily move from them to other water resources:

- *permanently wet area*
- *streams and waterways*
- *flood-prone areas*
- *natural wetlands*
- *drinking water bores and intakes*
- *open drains*
- *ponds, irrigation ponds, lakes* (MAF, 1997)

2.5 Policies and Suggestions Regarding Greenhouse Nutrient Solution Disposal in New Zealand

In this section, literature regarding greenhouse nutrient solution disposal in New Zealand is reviewed. In section 2.5.1, general policies and guidelines on sustainable management of natural resources are reviewed. In section 2.5.2 technical guidelines provided in *The Management of Nutrient Solution Released from Greenhouses: A Code of Practice* (COP) are discussed.

2.5.1 General Policies and Guidelines on Sustainable Management of Natural Resources

In New Zealand, the relationship between farming, sustainability, and New Zealand's environment has been considered carefully in recent years (PCE, 2004). The Resource Management Act 1991 (RMA) is the core legislation intended to help achieve sustainability in New Zealand. The RMA enables management at a regional level. Regional councils set their local regulations and policies about resource management as empowered by the Act. The Resource Management Act 1991 (RMA) states (in section 5-Appendix C) that everyone has a duty to avoid, remedy, or mitigate any adverse effects their activities may have on the environment.

Under the RMA the release of nutrient solution from soilless horticulture is classified as a discharge of a contaminant⁷ to the environment and its management requires resource consent (Lewthwaite et al., 2006).

The RMA does not allow any discharge of contaminants that might enter water to be made without resource consent, unless permitted by a rule in a plan. In the main greenhouse production areas (such as Auckland, Waikato, and Canterbury regions), Regional Councils have prepared soil and water plans. There are very detailed rules about sewage, animal effluent, and agricultural waste discharges. The discharges of sewage, wastewater and other contaminants are considered as discretionary activities which require resource consent applications (CHWWP, 2002; Earl, Scott, & Sanders, 2004; Veltman, Miller, Glennie, & Talbot, 2004; ARC, 2005a, 2005b). However, in New Zealand greenhouse nutrient solution discharge to land is proposed to be a controlled activity - that is a very

⁷ RMA 1991 (p.4), a "contaminant" is defined as:

- *Includes any substance (including gases, liquids, solids and micro organisms) or energy (excluding noise) or heat, that either by itself or in combination with the same, similar or other substances, energy or heat;*
- *When discharged into water changes or is likely to change the physical, chemical or biological condition of the water; or*
- *When discharged onto or into land or into air, changes or is likely to change the physical, chemical or biological condition of the land or air onto or into which it is discharged.*

simple consent. For the growers who are able to connect to a sewer to discharge nutrient solution to the sewerage system, this is considered a release option (ARC, 2005c).

Many Regional Councils have set the total amount of nitrogen that can be applied to land in a year. For example, in the Auckland region the limit is less than 200kg N/ha/year (ARC, 2005a). Therefore, when nutrient solution is discharged to land, the total amount (kg) of nitrogen should be considered. The calculation of the total amount of nitrogen includes nitrate-N, nitrite –N, and Ammonia-N.

However, when the nutrient solution is applied to outdoor crops as a fertiliser, the total amount of nitrogen application rate may be higher than the general requirement in regional plans. In this situation, the application should follow the guidelines in “*Code of Practice for Fertiliser Use*”. The “*Code of Practice for Fertiliser Use*” was published in 1998 by the New Zealand Fertiliser Manufacturers' Research Association. One of the purposes of this Code of Practice has been to provide a procedure which enables fertiliser users to employ sustainable practices specific to their situation (farm, orchard, forest), while ensuring they fulfill their responsibility under the RMA (NZFMRA, 2002). The Code summarises the principles for fertiliser use as a sustainable land management activity from both commercial and environmental perspectives. Also, there is a set of user guides to enable farmers to maximise production while minimising any adverse environmental effects in relation to fertiliser use.

2.5.2 The Management of Nutrient Solution Released from Greenhouses: A Code of Practice for Greenhouse Growers (COP)

In order to assist New Zealand greenhouse growers to release nutrient solutions in a way that does not add to nitrogen pollution of streams or ground water, “*The Management of Nutrient Solution Release from Greenhouse: A Code of Practice for Greenhouse Growers*” (COP) has been developed by the New Zealand Vegetable and Potato Growers' Federation (Vegfed). The COP is designed for the management of nutrient solutions

associated with soilless production of vegetable and flower crops in modern greenhouses. It describes the techniques of capturing the solutions and then releasing them when the conditions are suitable.

The suggestions and guidelines in the COP are similar to the general principles in other literature. However, as the COP is based on the New Zealand environment, there are some unique suggestions. The comparisons of general principles and the COP are presented in Table 2.2.

Table 2.2 A comparison of the general principles and the COP

Management stages	Key factors	Principle in literature	Guidelines in the COP
Growing stage	System design	The best hydroponic system is the recirculating system (Schnitzler, 2004; Tognoni, Pardossi, & Serra, 1998).	Well designed and maintained systems.
	Irrigation water	Ion content in the water affects nutrient solution EC (Donnan, 1994; Wilkerson, 1998) hence affects reuse cycle. Hygiene of the water directly affects probability of root disease happening hence the nutrient solution replacement frequency (Jones, 2004).	Recommend to use good quality water, treating water for control pathogenic fungi or removing contaminants when necessary
	Growing media	Growing media irrigation schedules vary (Logendra & Janes, 1999; Sonneveld & Voogt, 2001; White, 2006)	Medium type affect drainage percentage, e.g. Rockwool 30-40%, pumice 40-100%
	Crop growing stage	Nutrient solution recipe and irrigation schedule vary in different crop growing stages (Dorais et al., 2000; Hao et al., 2000; Li et al., 2001; Okano et al., 2000; Peet, 2004a)	No mention
	Solar radiation	In high light level conditions high supply and drainage volumes are required because a salinity problem will more likely occur. Solar radiation vary in seasons then the irrigation supply and drainage volume vary (Nichols, 1989; Valente et al., 1998; Jones, 2004; Peet, 2004)	Irrigation volume vary under different light level, e.g. in NZ greenhouse 2ml/m ² per joule ratio
	System hygiene	The efficiency of the sterilising units directly affects the nutrient solution reuse cycle and release frequency (Bell & Marchant, 1998; Van Os, 1999; Nederhoff, 2000).	Suggest to adopt UV units, Ozonation, heating treatment, filtration
Nutrient solution drainage collection and storage stage	Nutrient solution drainage management	Three styles, totally collected and reused, being collected and guide to disposal area, and run-to-waste (Tognoni et al., 1998).	Whether in recirculating systems or in run-to-waste systems, nutrient solution drainage needs to be collected and stored for reuse or for disposal.
	Nutrient solution storage capacity	The capacity should prevent any pollution due to overflow (Bell & Marchant, 1998).	Capacity for season: 4 months in winter and 2 weeks in summer.
Nutrient solution release stage	Nutrient solution disposal	Avoid nitrogen leaching to the ground water and surface water (Cornforth, 1998; McLaren & Cameron, 1996). Factors to consider: soil moisture, soil type, plants Options for disposal: reuse for crop, sewerage system (Bell & Marchant, 1998)	Suitable release site, release method, release timing.
	Nitrogen volume	Considered as the most significant and most frequent kind of groundwater pollution source from greenhouse nutrient solutions (McLaren & Cameron, 1996; MFE, 1997)	Same as other literature
	Record	No mention	The nutrient solution release information should be detailed recorded and be kept at least for five years.

In the COP, the nutrient solution management is based on three discrete stages, these are:

1. The growing stage;
2. The nutrient solution collection and storage stage;
3. The nutrient solution release stage.

In the crop growing stage, the COP outlines the factors which affect the nutrient solution discharge volume and frequency, including system design, irrigation water quality, growing media, solar radiation, and the ability to keep the water free of diseases. Also the COP describes some specific actions to limit the need to release nutrients, including maintaining the hydroponic system in sound condition, using high quality irrigation water, maintaining hygiene in recirculating systems, setting up an irrigation schedule based on solar radiation level, treating the water and solution for the control of pathogenic fungi and removing contaminants from the water and nutrient solution. These are all similar to the general principles in the literature. But the setting up of an irrigation schedule based on the crop growing stage, which is highlighted in the general literature, is not emphasized in the COP. The suggestions provide in the COP are based on the nutrient solution management for mature crops.

In the nutrient solution collection and storage stage, the COP states that whether a grower has a recirculating system or a run-to-waste system the nutrient solution drainage shall be collected and stored for reuse or for disposal. If the nutrient solution drainage is stored for disposal, it needs to be stored until the release site is in suitable condition for release. Regarding New Zealand weather conditions, there are rare chances in winter to release the nutrient solution, the nutrient solution storage period required is longer in winter and relatively shorter in summer. Therefore, the COP suggested that generally the nutrient solution needs to be stored in the system for two weeks in summer and four months in winter.

In the nutrient solution release stage, the COP focuses on the techniques that prevent or limit the ground and surface water pollution due to nitrogen leaching or runoff. When accessing a release site, soil type, ground water depth, contour, ground cover, sensitive

areas, and riparian strips should be considered. Similarly to the suggestions in other literature, the COP states that preferred nutrient solution release sites are places where surplus solution can be reused to provide water and nutrients for plant growth, such as pasture, outdoor crop, and forest. After a suitable release site has been selected, to avoid nitrogen leaching, risk assessments still need to be conducted before the nutrient solution release. The assessments include soil moisture information and weather information estimation.

In the COP, the nutrient solution release information should be detailed record and keep for at least five years. The required information includes hydroponic growing system description, irrigation water source information, release nutrient solution volume and composition laboratory analysis results, release nutrient solution volume, nutrient solution release site information, and nutrient solution release weather information. This detailed guideline was not emphasised in other literatures.

2.6 Summary of the Literature Review

In summary the existing literature suggest that to minimising the environmental impacts from nutrient solution release can be approached by: adopting efficient growing systems, managing nutrient solution efficiently in the growing system, and adopting suitable methods to dispose the nutrient solution (Figure 2.2).

- Adopting efficient growing systems

The primary approach to avoid nutrient solution directly discharges to land and water is to adopt efficient growing systems for hydroponic tomato growing. In general principle recirculating growing systems are preferred selection because they prevent the nutrient solution directly draining out of the system (Van Os, 1994; Tognoni et al., 1998; Van Os, 1999). Also, as the nutrient solution is collected and reused in recirculating growing system, its discharge volume and frequency is far lower than it is in run-to-waste systems

(Magen, 1999; Van Os, 1999; Bugbee, 2004; Dhakal et al., 2005). Base on New Zealand environment, the COP also suggests the well design and good maintenance greenhouse systems ensure reducing the nutrient solution discharge volume and frequency (Lewthwaite et al., 2006).

- Managing nutrient solution efficiently in the growing system

The management of the nutrient solutions in the growing system can be approached by reducing the nutrient solution drainage discharge volume and frequency. As a general principle, reductions in the nutrient solution discharge volume can be achieved by reducing the nutrient solution drainage volume, which is approached by setting up an efficient irrigation schedule based on the growing media type (Mason, 1990; Romer, 1993; Gunnlaugsson & Adalsteinsson, 1995; Adams, 1999), crop growing stage (Wilkerson, 1998; Peet, 2004a), and the greenhouse environment (Nichols, 1989; Valente et al., 1998; Peet, 2004b). Reductions in the nutrient solution discharge frequency can be achieved by increasing the nutrient solution reuse cycle, which is achieved by avoiding salinity accumulation in the solution (Donnan, 1994; Bell & Marchant, 1998; Magen, 1999; Savvas & Adamidis, 1999; Kempkes & Stanghellini, 2003) and avoiding root disease occurrence (Van Os, 1999). Salinity accumulation can be avoided by using high quality irrigation water (Mason, 1990; Runia, 1995; Johnson et al., 1999; Magen, 1999; Schwarz et al., 2004), adjusting the nutrient solution concentration and composition in different crop growing stages and growing seasons (Anon, 2000; Dorais, et al., 2000; Hao et al., 2000; Okano et al., 2000; Li et al., 2001; Peet, 2004a), and removing unwanted ions in the reused nutrient solution (Donnan, 1994). Root disease occurrence can be avoided by maintaining the system's hygiene and sterilising the irrigation water and nutrient solution to ensure there are no root disease pathogens inside (Donnan, 1994; Runia, 1995; Schnitzler, 2004). In the COP, suggestions are quite similar to those in the general theories. Based on the New Zealand environment, the COP emphasises setting up the irrigation schedule in response to the growing season and growing media, using good quality irrigation water and fertiliser, and maintaining the system's hygiene (Lewthwaite et al., 2006).

- Adopting a suitable method to dispose of the nutrient solution

As a general rule, adopting a suitable disposal method to minimise the nitrate nitrogen leaching includes discharging the nutrient solution to suitable release sites (MFE, 1997; MAF, 2000), suitable timing of the discharge (Cornforth, 1998; NZFMRA, 2002), and adopting suitable release methods (McLaren & Cameron, 1996). The best option for nutrient solution release is to reuse it as fertiliser to irrigate outdoor crops, pasture, forestry and so on (Bell & Marchant, 1998; RIRDC, 2001, ARC, 2005c). When nutrient solutions are discharged to land, a risk assessment must be conducted to ensure that the site is in a suitable condition for release (NZFMRA, 2002). The COP suggests that to ensure that the nutrient solutions can be discharged at a suitable time, it requires storage in the system and hence the system's storage capacity should be considered (Lewthwaite et al., 2006). When there is no suitable release site available or the system's storage capacity is inadequate, the nutrient solution can be discharged as wastewater (Bell & Marchant, 1998) for which resource consent must be obtained (RMA, 1991; ARC, 2005a).

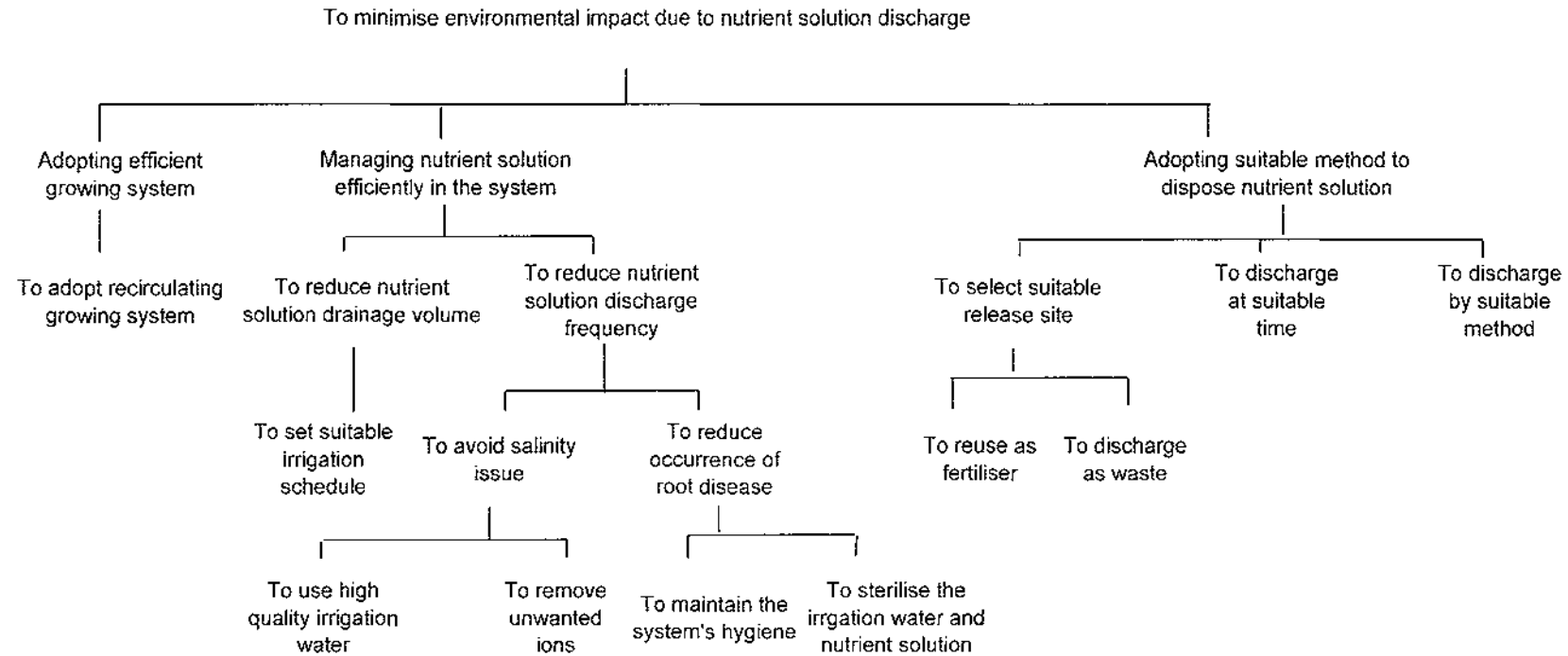


Figure 2.2 Explanatory model of minimising environmental impact due to nutrient solution discharge

3. Methodology

According to the theories in the literature, reducing the environmental impacts of greenhouse nutrient solution release can be approached by adopting an efficient growing system, managing nutrient solution efficiently in the growing system, and adopting suitable methods to dispose of nutrient solution. However, little was known about how New Zealand commercial growers manage nutrient solution in existing production conditions. The best way to obtain detailed information was talk to the growers directly. Therefore a multiple-case study was selected as the research method in this project. In this chapter, selection of the research strategies, case study design, and multiple-case study process are discussed.

3.1 Selection of Research Strategies

Social research includes science, theory and data collection (David & Sutton, 2004). Empirical social research is a practical activity. It involves the collection, exploration and reporting of information about people and societies (Yates, 2004). There are different approaches and strategies for conducting social science research. Yin (2003) indicated that research questions, research propositions (if any), research units of analysis, the logic linking the data to the propositions, and the criteria for interpreting the findings, are the five most important components in research design. Maxwell (2005), however, highlighted the research goals, the conceptual framework of the research, research questions, research methods, and research validity as the five key components when designing research. Within all those components, the process of identifying a research question is always an essential first step in any project (Yin, 2003; David & Sutton, 2004; Maxwell, 2005).

Yin (2003) indicated five major research strategies that are used in social science research: experiments, surveys, analysis of archival information, histories, and case studies. He stated that three factors determined the research strategy a researcher might use. The first

of these is the form of the research question, the second one requires control over behavioural events, and the last one is focused on contemporary events. Therefore, Yin (2003) developed a matrix (Table 3.1) to help researchers select the most suitable research strategy for their research project.

Table 3. 1 Relevant situations for different research strategies. Source: Yin (2003).

Strategy	Form of research question	Requires control over behavioral events	Focuses on contemporary events?
Experiment	How, why	Yes	Yes
Survey	Who, what, where, how many, how much	No	Yes
Archival analysis	Who, what, where, how many, how much	No	Yes/no
History	How, why	No	No
Case study	How, why	No	Yes

The first criterion Yin (2003) uses to select a research strategy is the form of the research question posed. There are five types of research questions: who, what, where, how and why. Normally, “what” questions can be answered by all five research strategies. “Who”, “where”, “how many” and “how much” questions are best answered by survey and archival analysis strategies. “How” and “why” questions, which are more explanatory in nature, are best answered using case study, history and experimental research strategies. In this research, the research questions included: “*How* do greenhouse growers manage nutrient solution in greenhouse systems?” “*Why* do some growers manage nutrient solution better than others in terms of minimising the environmental impacts of nutrient solution release” and “*How* can greenhouse growers improve their performance to better manage the nutrient solution in greenhouse production?” A survey can answer “what” questions but cannot answer “how” questions, hence this strategy was discounted in this

research. The archival strategy cannot answer “how” and “why” questions so it was also discounted as a strategy for this research.

The second criterion used by Yin (2003) to determine a researcher’s research strategy is the level of control the investigator requires over the behaviour of the subject of the research. An experimental strategy allows the researcher to manipulate the behaviour of research subjects. However, for this research, the researcher wanted to investigate the nutrient solution management of growers in a natural setting, so control over behavioural events was not required. Therefore, the experimental research strategy was also discounted in this study.

The final criterion used by Yin (2003) to determine the most appropriate research strategy was the degree of focus on contemporary as opposed to historical events. History is a preferred strategy when access to relevant subjects is not possible. In such circumstances an investigator must rely on primary documents, secondary documents, and cultural and physical artefacts as the main sources of evidence (Yin, 2003). For this research, the focus is on the contemporary events-management practices of existing growers. Also, access to the relevant subjects, such as greenhouse properties and greenhouse growers, is possible. Therefore, the history research strategy was also discounted for this project.

Using Yin’s (2003) criteria, it can be seen that the most suitable research strategy for this study is the case study. This is because a case study is preferred for examining contemporary events, but only when the relevant behaviours cannot be manipulated. The unique strength of the case study is its ability to deal with the full variety of evidence, including documents, artefacts, interviews, and observations to ensure that the researcher will acquire an in-depth understanding of the events (Yin, 2003). It is also considered as one of the significant strategies used in qualitative research (Creswell, 2002). Merriam (1998) also stressed that the case study is a particularly suitable design if the researcher is interested in process-and the focus of this study is the growers’ nutrient solution management process. Therefore, the case study was the preferred research strategy for this study. The case study design and methods are discussed in the following section.

3.2 Case Study

Yin (2003, p.13) defined the *case study* as *an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and the context are not clearly evident*. Research using case studies can be classified into four main types based on two important research design decisions (Yin, 2003). The first decision is whether to undertake a single or a multiple case study design. The second is whether the study is an holistic or an embedded case study (Yin, 2003). These decisions can be represented in a matrix (Figure 3.1)

	Single-case design	Multiple-case design	
Holistic (single unit of analysis)	Context Case	Context Case	Context Case
		Context Case	Context Case
Embedded (multiple units of analysis)	Context Embedded unit of analysis 1 Embedded unit of analysis 2	Context Embedded unit of analysis 1 Embedded unit of analysis 2	Context Embedded unit of analysis 1 Embedded unit of analysis 2
		Context Embedded unit of analysis 1 Embedded unit of analysis 2	Context Embedded unit of analysis 1 Embedded unit of analysis 2

Figure 3. 1 Basic types of designs for case studies. Source: Yin (2003)

A single case study is justifiable under three conditions: when it presents the critical case in testing a well-formulated theory, when the case presents an extreme case or a unique case, and when the case study is a revelatory case (Yin, 1994). Multiple case studies can be used to compare the similarities and differences between cases (Yin, 1994). They have distinct advantages and disadvantages in comparison with single case studies (Yin, 1994). The evidence from multiple cases is often considered more compelling, and the overall study is therefore regarded as being more robust (Yin, 1994). However, the conduct of a multiple case study can require extensive resources and time (Yin, 1994).

The second decision a researcher must make about the case study design is whether to use an holistic or an embedded design (Yin, 2003). Embedded cases tend to be the norm in qualitative research and encompass cases where there is more than one unit of analysis. That is, there are several components within the case that are investigated. An holistic case is one where the case itself is the units of analysis and there are no embedded units of analysis (Yin, 2003). For this research, an embedded multiple-case study was selected because there are several units of analysis. The embedded units are growing systems and nutrient solution management practices adopted by the case study growers. In the next section, the multiple-case study process is discussed.

3.3 Multiple Case Study Process

Yin (1994, 2003) separated the multiple case study approach into three stages. The first stage he called the “define and design stage”. It includes theory development, case selection, and the design of the data collection protocol. The second stage he formed is the “prepare, collect, and analyse stage”. It includes conducting individual case studies and writing individual case reports. The final stage Yin described as the “analyse and conclude stage”. It includes drawing cross-case conclusions, modifying theory, developing policy implications, and writing cross-case reports (Yin, 1994, 2003). A multiple case study approach can be described as in Figure 3.2, sourced from Yin (2003).

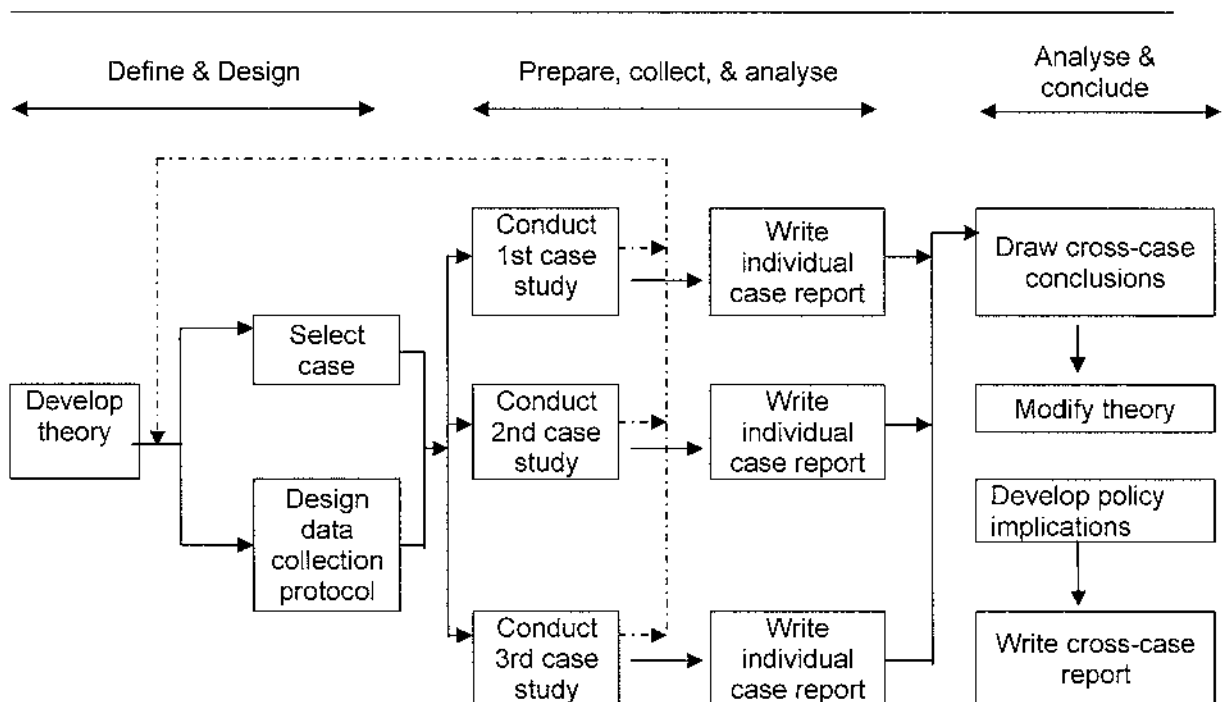


Figure 3. 2 Multiple case study approach. Source: Yin (2003)

In this research, the multiple-case study process followed this theory given by Yin. Details are presented in the following section.

3.3.1 Case Study: Define and Design

There are three steps in a case study's define and design stage: develop theory, select case, and design data collection protocol.

3.3.1.1 Develop theory

The first step of this multiple case study was theory development. Maxwell (2005) indicated that theory development enables the researcher to develop a conceptual framework for the research. In this research, theory development was achieved by undertaking a literature review on greenhouse tomato nutrient solution management. Factors that needed to be considered in each management stage, specific practices related to minimising the volume and frequency of nutrient solution drainage, methods for

reducing the environmental impacts due to the nutrient solution release, and the regulations and guidelines relevant to resource consent in New Zealand were reviewed. The findings from the literature were used as a conceptual framework to help select the cases and design the data collection protocol. The case studies were then compared with the literature review to identify areas where practice agreed with theory, or discrepancies existed.

3.3.1.2 Selection of Cases

Yin (2003) indicated that when using a multiple-case study design, the researcher has to consider the number of cases for the research. Any use of multiple-case designs should follow a designed replication, which means that each case must be carefully selected so that it predicts similar results (a literal replication), or produces contrasting results but for predictable reasons (a theoretical replication).

There are only a few examples in the literature, where detailed descriptions of nutrient solution management in commercial greenhouses in the New Zealand tomato growing industry are provided. Therefore details of which practical technologies the growers are using and whether or not they could meet the standards described in the literature remain unclear. According to the greenhouse management theories, nutrient solution management is largely determined by the hydroponic system's design and the growers' management practices (Mason, 1990; Smith, 1999; Bugbee, 2004; Jones, 2004). Minimisation of the environmental impacts of greenhouse nutrient solution release can be achieved by reducing the nutrient solution release volume and frequency, releasing the nutrient solution to suitable release sites, and adopting suitable methods to release the nutrient solution (Chartzoulakis & Michelakis, 1988; Tognoni & Serra, 1994; Van Os, 1994; Jeannequin & Fabre, 1995; Cameron, Di, & McLaren, 1997; Bell & Marchant, 1998; Bugbee, 2004; Giacomelli, 2004; Anton, Montero, Munoz, & Castells, 2005; Lewthwaite et al., 2006).

The literature had shown that adopting a recirculating growing system can efficiently reduce nutrient solution release to the environment (Mason, 1990; Smith, 1999; Bugbee, 2004; Jones, 2004). Therefore it was assumed that greenhouse growers who adopt recirculating growing systems might better manage the nutrient solution in terms of minimising the release frequency and volume than those growers who adopt run-to-waste growing systems.

In addition to the growing system design, the literature had shown that growing media type, irrigation water quality, and growers' technical practices affect the efficiency of nutrient solution management (Chartzoulakis & Michelakis, 1988; Jeannequin & Fabre, 1995; Bell & Marchant, 1998; Bugbee, 2004; Anton et al., 2005; Lewthwaite et al., 2006). Therefore, it was assumed that by growing tomatoes in different growing systems, using different growing media, using different irrigation water, and adopting different technologies; the nutrient solution release volume and frequency could be different.

Generally large-scale modern greenhouse growers have the abilities to set up and maintain advanced control and monitoring systems. Hence they can adopt high technologies to manage nutrient solution. Small-scale greenhouse growers, however, may not have the abilities to set up advanced control and monitoring systems. Hence they have to adopt relatively low technologies to manage nutrient solution. Therefore, it was assumed that large-scale modern greenhouse growers might manage better nutrient solution than small-scale greenhouse growers because they have better production conditions, and the possibility of adopting higher level technologies.

Although moving to larger size growing areas and adopting more intensive technologies are trends in the New Zealand greenhouse industry, many greenhouses are still small-scale family-based enterprises (Vegfed, 2004), and most of the small-scale growers are using run-to-waste systems (VanVugt, personal communication, February 2006). Therefore, it was considered necessary to investigate how greenhouse growers manage activities under different production conditions in order to identify the opportunities for them to improve their performance in the future.

The case study number was decided as three. It was assumed that if a greenhouse property has a recirculating system with modern advanced control and monitoring equipment, the grower's nutrient solution management practices would closely match the requirements in the COP. If a greenhouse has a recirculating system but no advanced control and monitoring equipment, the grower's nutrient solution management practices would be less likely to match the requirements in the COP. If a greenhouse has a run-to-waste system, the grower's nutrient solution management practices would fall far short of the requirements in the COP. In addition to the system design, production scale, growing media type, irrigation water source, and technology level were all considered during case selection because these factors were indicated as being important in nutrient solution management in the literature.

A number of greenhouse growers were contacted by telephone before the case selection. The contact list was obtained from the "*Greenhouse tomato crop protection and nutrient disposal survey for fresh tomato sector of Vegfed-2004*" (Martin, 2004). During the telephone contact, the researcher first introduced herself and described the research topic briefly to the growers. The growers were then asked if they were willing to participate in the study. If a grower was happy to assist the researcher, she or he was then asked to provide some basic information about their greenhouse system such as location, growing area, growing system, irrigation system, media type, irrigation water source, and nutrient solution release frequency.

After the telephone contacts, three greenhouse enterprises which the researcher considered represented the current New Zealand greenhouse industries were selected as case studies. The selected cases were all located in the North Island of New Zealand. This was because firstly, greenhouse tomato industries in New Zealand are mainly located in the North Island (Vegfed, 2004). Secondly, considering the research funding and time were limited, all the cases were selected in North Island to ensure the researcher's convenience of accessing the case study growers and conducting interviews and fieldtrips.

Case Study One was a large-scale greenhouse enterprise. Its nutrient supply system was a modern computer control and monitoring recirculating system. The grower continuously reuses the nutrient solution in the growing system and releases it only in an emergency. Therefore the nutrient solution is managed using state of the art technology efficiently. Case Study One tries to reduce the environmental impact of greenhouse nutrient solution release by minimising the nutrient solution release frequency. It was assumed that Case Study One would fully satisfy the requirements set out in the COP.

Case Study Two was a small-scale family-based greenhouse enterprise that lacked advanced computer control and monitoring systems. The grower produces tomatoes in a recirculating growing system. Unlike Case Study One who releases nutrient solution into the environment only when an emergency occurs, Case Study Two regularly releases nutrient solution into the environment. As Case Study Two has to release nutrient solution regularly during production, it would have poorer nutrient solution management practices. It was assumed that Case Study Two was one of the greenhouse enterprises which could less likely to satisfy the requirements set out in the COP.

Case Study Three was a small-scale greenhouse enterprise that lacked advanced computer control and monitoring systems. Case Study Three growers produce tomatoes in a run-to-waste growing system. The nutrient solution drainage was not recirculated but instead was released directly into the environment on an almost daily basis. It was assumed that Case Study Three would the least likely to satisfy the requirements set out in the COP.

3.3.1.3 Design of Data Collection Protocol

There are six sources of evidence in a case study, including documentation, archival records, interviews, direct observations, participant-observation, and physical artefacts (Yin, 1994, 2003). The various sources are highly complementary, and in a good case study therefore as many as possible will be used (Yin, 1994, 2003). Interviews are an essential source of case study evidence because most case studies are about human affairs (Yin, 1994, 2003). In an interview the researcher and the participants develop a shared

perspective and understanding of the topic under discussion (Yates, 2004). The interview can be semi-structured or unstructured (Yates, 2004). In semi-structured interviews, a pre-set agenda is used to define the flow of the interview. In contrast, in an unstructured interview, no pre-set agenda is used (Yates, 2004).

In this research, in order to obtain an in-depth understanding of the nutrient solution management process used in each selected case, the researcher needed to share her perspective and understanding of the topic under discussion with each selected interviewee. Therefore, a semi-structured interview was adopted as the primary data collection method. In addition, documentation and archival records were collected as secondary data. Documentation sources consisted mainly of internet references relevant to the topic. Archival records mainly included internal records from each case such as the nutrient solution recipes, supply volume records, drainage monitoring records, and the release information records. Field observations were also conducted throughout the case study. The objectives of the field observations were:

- 1) to observe the greenhouse growing system, irrigation system, nutrient solution supply, collection, storage, and treatment facilities in the properties;
- 2) to observe the nutrient solution management technical details during production, particularly the management activities in different stages, such as in different crop growing stages.
- 3) to confirm the information obtained from the interviewees.

Each selected case study grower was interviewed four times. Considering that the main research objective was to investigate whether the commercial greenhouse grower's nutrient solution management activities could meet the standard requirements both in the literature and in the COP, the interview questions were developed based on the nutrient solution management theories in the literature and the guidelines presented in the COP.

3.3.2 Case Study Data Preparation, Collection, and Analysis

There are two steps in this case study stage, including interview preparation and data collection.

3.3.2.1 Interview Preparation

After the cases had been selected, joint letters from Massey University and Vegfed were sent to the case study growers to confirm that they were still keen to be involved in the study and willing to sign a confidentiality agreement. Once these points were confirmed, emails were sent to the growers to arrange the date of the first interview. The confidentiality agreement, the general focus of the research, and the interview questions were also sent by email. Then the date of interview was confirmed by telephone.

3.3.2.2 Data Collection

After the interview dates had been arranged, the researcher visited the properties as arranged. Before asking the formal interview questions, the researcher introduced herself to the interviewees. Then the researcher provided a brief background, objectives, and scope of the research to the interviewees through icebreaking conversations. The purpose of the icebreaking conversation was to develop rapport between the researcher and the growers. This was because when conducting interviews, gaining trust is essential for success (Fontana & Frey, 1994). Therefore the development of rapport with the interviewees is critical in the first stages of the research and first impressions were considered important. After rapport had been built, the researcher began to have an open discussion with the interviewees. Tape recorders were used to record the conversation, with the permission of the interviewees, in order to obtain full detailed information during each visit. Notes were taken by the researcher to summarise key points made by the interviewees during the interview.

During the visit, field observations were also made after each interview conversation. With the growers' permission, photos were taken during field observations.

The objectives of the first interview were:

- 1) to build rapport with the selected interviewee;
- 2) to obtain an overview understanding of the selected greenhouse property, including greenhouse size, crops, cropping schedule, and irrigation systems.

The interview questions in the first interview were focused on three aspects:

- 1) the background information about the interviewee;
- 2) the cropping system;
- 3) the irrigation system.

After the first interview, the transcript of the interview was analysed and a summary of the interview was sent to the grower by email for verification. After the researcher had received an answering email from the growers, the date of the second interview was arranged by email along with the question set for the next interview. Then the second interview date was confirmed by telephone.

The objectives of the second interview were:

- 1) to verify the information obtained from the first interview;
- 2) to obtain an understanding of the grower's nutrient solution management process.
- 3) to identify factors which need to be considered by the growers in different management stages, including factors in the crop growing stage, nutrient solution collection and storage stage, and nutrient solution release stage;

The interview questions on the second interview focused on three aspects:

- 1) nutrient solution management in the crop growing stage;
- 2) nutrient solution management in the collecting and storage stage;
- 3) nutrient solution management in the release stage;

The whole sets of the first and the second interview questions are shown in Appendix 1.

After the second interview, the first drafts of each case study report based on the information obtained in the first two visits were written and sent to the interviewees by email. The date of the third interview was arranged by email and then confirmed by telephone.

The objectives of the third interview were:

- 1) to confirm the information gathered from the second interview;
- 2) to openly discuss the case study report drafts with the interviewees. Then gather any necessary information which had been missed in the previous interviews.

After the third interview, detailed case study reports for each case study were developed and sent to the interviewee by email. The date of the fourth interview was arranged and confirmed by telephone. The objective of the fourth interview was to confirm the fully detailed information obtained in the previous visits. Since the third interview and the fourth interview focussed on verifying the case study report and identifying the omissions, there were no interview question sets prepared before these interviews.

3.3.3 Data Analysis

There are two types of case study data analysis: within-case and cross-case analysis (Yin, 2003). Within-case analysis could be considered as a prior requirement component to cross-case analysis (Huberman & Miles, 1994). In this research, the data analysis followed the suggestions given by Yin (2003) and Huberman and Miles (1994). After the within-case analysis and cross-case analysis, a comparison of the findings from the case studies and the principles in the literature was conducted in the final stage.

3.3.3.1 Within-case Analysis

The within-case analysis method used in this research was the qualitative data analysis procedure advocated by Dey (1993). This is a process that comprises these steps: data description, data classification, and data connection. Each step is discussed in the following sections.

3.3.3.1.1 Data Description and Classification

Dey (1993) indicated that qualitative data analysis consists of a three-step process that comprises: describing, classifying, and connecting. Data description is the first step of the data analysis, a thorough description of the phenomena under study is developed from the data which may include interview transcripts, documents, and field observations (Dey, 1993). Classification is used to organise bits of data into categories based on relevant characteristics, so that useful comparisons between these data bits can be made for interpretation and explanation of the phenomena in the study (Dey, 1993). Classification can be viewed as a process that converts data into categories (Dey, 1993). The first step in the classification process is to read over the literature review and identify important concepts and their definitions. The next step is to read the transcript line by line and compare the data to existing concept definitions. For example, the topic is *nutrient solution management in greenhouse tomatoes*. If a data-bit “*formulating the nutrient solution*” matches the definition of a category “*nutrient solution supply management*”, it is classified as an instance of that category. If the data-bit does not fit into an existing category-for example “*nutrient solution drainage collection*” does not fit into “*nutrient solution supply management*” but is relevant to the research topic, a new category “*nutrient solution drainage management*” is named and defined. If the data-bit is an instance of an existing sub-category such as “*nutrient solution supply management*”, it is classified. If the data-bit is not an instance of an existing sub category but is purely an instance of the high level category, it is classified; otherwise a new sub category would be

created and classified. The sample process of classification in this research can be presented as decision rules in Figure 3.3.

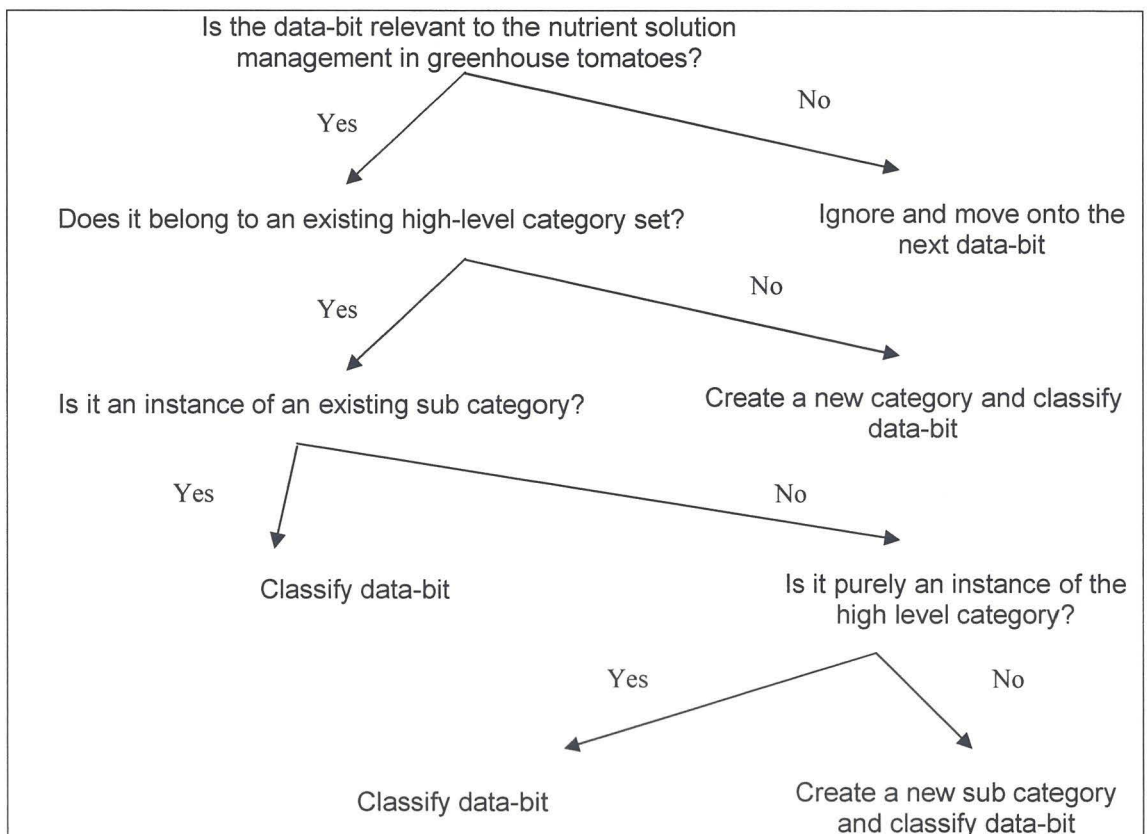


Figure 3. 3 A sample of decision rules used in the data classification process. Source: Dey (1993)

3.3.3.1.2 Connection

Once the category hierarchy has been developed, the next step is to identify connections between categories. Connection involves identifying and defining the relationships between categories in the data (Dey, 1993). There are two types of relationships in a research: formal or logical relationships and substantive relationships (Dey, 1993). Formal or logical relationships are based on similarities or differences. They are used to classify similar categories, for example "*a recirculating growing system is different from non-*

recirculating growing in terms of nutrient supply". Substantive relationships include causal relationship, explanatory relationship, and chronological relationship (Dey, 1993). They are not based on logic but tend to link dissimilar categories. In this research, causal relationships were used to present causes and effects. For example, during the day time, *"the solar radiation increases"*, therefore *"the tomato plants' water consumption increases"*. Explanatory relationships were used to present the technical activities the grower used to achieve a particular purpose of management. For example, growers *"use high quality irrigation water"* in order to *"avoid ion accumulation in the nutrient solution"*-which they need to do in order to *"increase the nutrient solution reuse cycle"*. Similarly, how growers *"increase the nutrient solution reuse cycle"* can be achieved by *"avoiding ion accumulation in the nutrient solution"*, to *"avoid ion accumulation in the nutrient solution"* can be achieved by *"using high quality irrigation water"* (Figure 3.4).

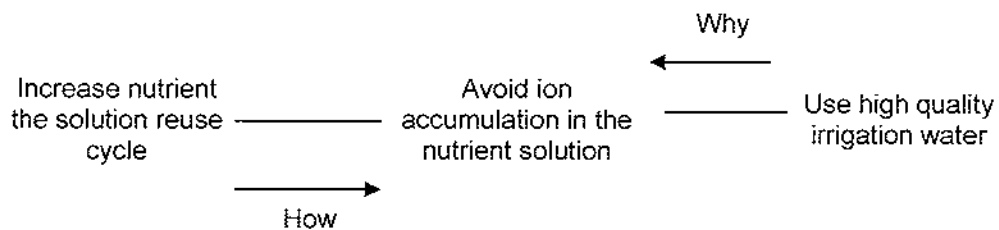


Figure 3. 4 Sample explanatory linkages of technical activities to ensure reduction of nutrient solution drainage.

Chronological relationships were used to show a sequenced nutrient solution management process used by greenhouse growers, such as the nutrient solution management process moves from the nutrient solution supply stage to the nutrient solution drainage management stage, and then to the nutrient solution disposal stage.

Case study reports for individual cases were written after the interviews had been completed. The process used by the selected greenhouse growers to manage nutrient solution in each property was described in detail. Further data analysis was conducted in the following stage.

3.3.3.2 Cross-case Analysis

Once the within-case analysis is completed, cross-case analysis is used to determine why different cases produced similar or different results (Yin, 2003). The purpose of the cross-case analysis was to develop understanding of the phenomena in the study (Eisenhardt, 1989). After the individual case study reports had been written, the findings from each case were compared to each other. Differences between cases were discussed, and explanations for the differences were proposed. After that, results of the cross-case analysis were used to compare and contrast with the conceptual framework built from the literature review.

3.3.3.3 Comparison to Literature

In this research, the conceptual framework was built up based on the literature review. After cross-case analysis, the summaries of the case studies were compared with the general theories in the literature and the guidelines in the COP. The key aspects for comparison were the system design and nutrient solution management process, which included the nutrient solution supply management, the nutrient solution drainage management, and nutrient solution disposal. Reasons for similarities and differences between the case studies and the general theories, and the guidelines in the COP were identified.

4. Case Study Report

In this chapter, three case study reports are presented. Each case study report includes five sections, which are “*Case Description*”, “*Hydroponic Systems*”, “*Nutrient Solution Supply management, Nutrient Solution Drainage Management*”, and “*Nutrient Solution Disposal*”.

4.1 Case Study One

The Case Study One greenhouse property is located in an upper North Island urban area. The nutrient solution management information in this section was obtained by interviewing one of the growers working on the property. The interviewee, who has a tertiary qualification in horticultural science and has been involved in the greenhouse industry for six years, will be referred to by the pseudonym “Grower One” in the following section.

All the greenhouses in Case Study One are modern environmentally controlled glasshouses with up-to-date online computer control and monitoring systems. Case Study One growers manage nutrient solutions in a recirculating media system. They minimise the nutrient solution release volume and frequency by adopting high level technologies and advanced equipment. In Case Study One, the nutrient solution continuously recirculates and is released only in an emergency. Grower One claimed that in the last three years, there has been no nutrient solution release in the greenhouses. Therefore, the enterprise was considered to have the highest technical level in terms of minimising nutrient solution release. As such it was selected as one of the case studies.

4.1.1 Case Description

The total greenhouse area is approximately 40,000 m². Only tomatoes are produced in the greenhouses. Each greenhouse covers approximately 10,000 m², is 5 to 6 years old and is approximately 4.5 metres to the gutter. The covering material is glass and the growing system is a hydroponic media system. Tomato plant stems are hung from horizontal wires about three metres above the ground. The wire height in the greenhouse is 3.8 metres.

There are two kinds of growing media, coco-peat and rockwool, both are contained in growing slabs. There are around 5,000 media slabs in each 10,000 m² sized greenhouse. Each slab, which is approximately one metre long and 10-15 litres in volume, has two plant cubes. Each plant cube has one top-dripper for irrigation supply.

The crop densities, which are controlled by taking off the laterals of the plants, vary between seasons as the solar radiation conditions change. In winter⁸, the density is 2.2 plants⁹ per square metre, while in summer it is 2.7-3.3 plants per square metre.

Case Study One does not use bore water because the property is located very near the sea, and bore water has a salinity problem. The town water supply is not big enough to supply the property's water requirements so irrigation water is sourced from rainwater collected from the greenhouse roofs together with the town water supply. Rainwater is stored in an outdoor uncovered lined pond near the greenhouses and it is the primary source of irrigation water. However, at particular times of the year-such as in summer-the water supplied by rainfall may be inadequate and during these periods, 50% of the irrigation water comes from rainwater and 50% comes from town water. During a typical year, around 70% of the irrigation water comes from rainwater and 30% comes from the town water supply.

⁸ For this case, there is no exact definition of spring, summer, autumn and winter for seasons, but Grower One distinguishes two growing seasons, summer (October to March) and winter (April to September).

⁹ For this case, "*plants*" refer to the number of plant stems.

According to the results of laboratory analyses, Grower One stated that the quality of both rainwater and town water is good and consistent. There are no sodium or chloride problems so no special treatment for removing ions was required. However, as the rainwater is stored in an outdoor uncovered pond, Case Study One uses slow sand filters, screen filters, and UV treatment to sterilise the rainwater before it is used for irrigation.

The property produces one crop per year. There are two crop planting scenarios, one is based on a late July planting to June and the other is April planting to March. The annual yield is around 45-60kg/m², depending on the planting season. Interviews for this case study were conducted during the July to June cropping cycle.

In early July, new tomato crops are transplanted from the propagator into new growing media slabs. After the tomato plants have been transplanted, there is no picking in the first seven to eight weeks. At this stage, the young tomato crops are basically in a vegetative growing phase. Picking normally begins in the 8th week after the crop has been transplanted. At this stage, the tomato crops become mature and are in a generative growing phase. The harvest period is from September until early June. During production, after the plants have grown above three metres, they are laid down and continue to grow reaching a final length of around ten metres.

In late June, two weeks are arranged for cleaning up the greenhouses. In these two weeks, all the old crops and used media slabs are removed. The used coco-peat media will be passed to a compost manufacturer for secondary use but the rockwool media do not have a secondary use, and payment by weight must be made for their disposal. The greenhouses are emptied and sterilised. After that, new media slabs are placed into the clean greenhouses and prepared for the next crop cycle.

4.1.2 Hydroponic System

The hydroponic system in Case Study One is a recirculating system. The flow of nutrient solution in such an irrigation system is illustrated in Figure 4.1.1.

Irrigation water, which is supplied from two sources (town water supply and rainwater), is stored in the raw water tank (1), which has a capacity of approximately 400 m³. To ensure that the irrigation water is hygienic, rainwater is treated through a slow sand filter (2), a screen filter (3), and an UV unit (4) before it flows to the raw water tank. Fresh nutrient solution A (5) and solution B ¹⁰(6) are stored in different fresh nutrient solution storage tanks (2 m³ each tank). Fresh nutrient solutions (A and B) flow into a 1 m³ size mixing tank (7), where they are blended with fresh water and the reused nutrient solution. Each greenhouse has its own nutrient solution A and B storage tanks and a mixing tank. After blending, pH adjustment, and EC adjustment the mixed nutrient solution is pumped out of the mixing tank through a sand filter, a screen filter and then supplied to the tomato crops in the (8) greenhouses through a drip system. During production, some nutrient solution drainage comes out of the growing media. The nutrient solution drainage is collected and stored in a central nutrient solution drainage storage tank (9), which has a capacity of approximately 200 m³ of which 1/3 would normally be kept free. The collected nutrient solution drainage is pumped out of the central drainage storage tank through a sand filter, a screen filter, and a UV unit for sterilising. The sterilised solution is stored in four reused nutrient solution storage tanks (10), each of which has a capacity of 20 m³ each. Each greenhouse has its own reused nutrient solution storage tank. The reused nutrient solution is then pumped to the nutrient solution mixing tanks, where it is combined with fresh water and fresh nutrient solution, and the cycle starts again. When serious root disease has been found, the drained solution can not be recycled and is thus pumped out of the central drainage storage tank and spread to a small area of lawn near the greenhouse (11).

¹⁰ Solution A contains calcium and iron chelate, solution B contains other fertilisers.

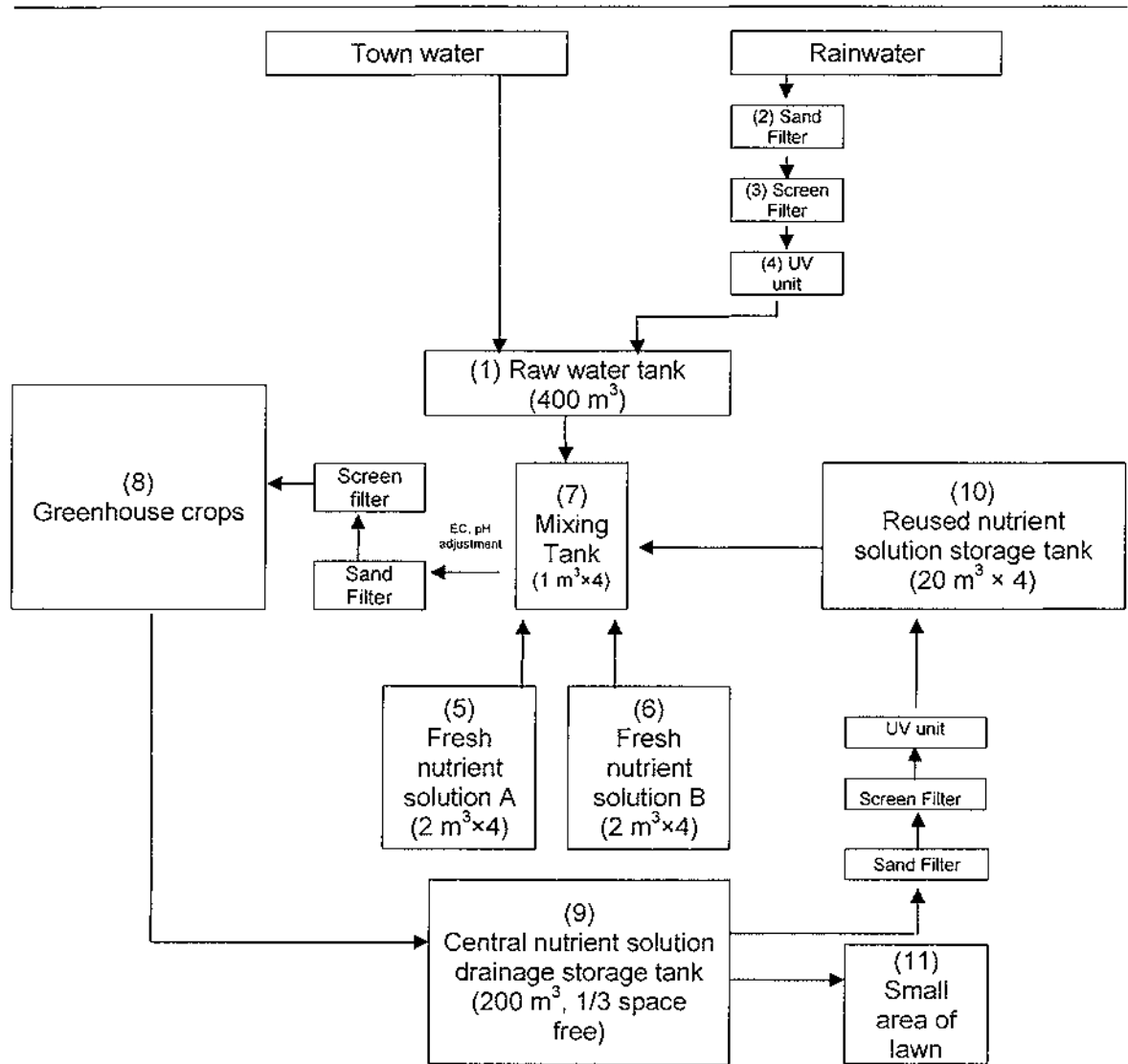


Figure 4.1. 1 Case Study One nutrient solution flow diagram

In Case Study One, there is one irrigation system to supply nutrient solution to the whole growing area. The processes for nutrient solution management, including nutrient solution supply management, nutrient solution drainage management, and nutrient solution disposal, are presented in the next section.

4.1.3 Nutrient Solution Supply Management

In this section, the technical details of Case Study One's nutrient solution supply management will be presented. In section *4.1.3.1 Formulation and Adjustment*, details of the nutrient solution formulation and adjustment, which affects the composition of the supplied and drained nutrient solution, are provided. In section *4.1.3.2 Nutrient Solution Supply*, details of the nutrient solution supply management, which affect the nutrient solution supply and drainage volume are described.

4.1.3.1 Formulation and Adjustment

In Case Study One, the nutrient solution supply for the tomato crops is prepared by Grower One. The fresh nutrient solution includes two parts, solution A and solution B. Each greenhouse has its own fresh nutrient solution storage tanks because the nutrient solution recipes vary between tomato varieties, and growing media.

The initial recipe was obtained from the internet, then Grower One adjusted the composition based on several factors, including variety, growing media, crop growing stage, and type of growing season.

A range of tomato varieties is grown in Case Study One's greenhouses and the nutrient requirements differ between varieties. For example, potassium requirements vary with fruit size. Therefore varieties with larger fruit sizes require more potassium, while recipes for smaller sized fruit require less.

Grower One pointed out that inert growing media such as rockwool generally have few effects on the nutrient solution supply. However, organic growing media such as coco-peat contain a certain amount of available nutrient such as potassium, calcium, magnesium, and nitrogen. For this reason the specific nutrient formulation used needs to be calculated with reference to the growing media used.

Crop growing stage is another key factor in nutrient solution formulation. Nutrient solutions are adjusted frequently during a growing cycle. Generally, a sample of nutrient solution drainage is sent to a laboratory for analysis of pH, EC, and individual nutrient elements' concentration every two to three weeks. Grower One adjusts the nutrient solution recipe according to the results of this analysis. However, at a certain crop growing stage-such as in the three to four weeks leading up to the first picking-extreme care is needed in nutrient solution management. Grower One explained that this is because through this period, tomato plants change from having vegetative growth to having generative growth. There are also extreme changes in the nutrient requirements of the crops. If the nutrient element ratio can not be adjusted promptly during this period, it affects plant growth badly. Therefore, during this period nutrient solution recipes are adjusted based on the manager's experience and the plant performance rather than only on the results of laboratory analyses.

"If you sit on your hands waiting for the lab to return analysis results, then you will have waited too long."... "Even then it is not foolproof; you can still get yourself in trouble by doing guess work rather than relying on numbers."

When monitoring the nutrient solution, Grower One looks not only at the individual nutrient elements' concentration, but also at the supply and nutrient solution drainage's pH and EC. The pH of the nutrient solution supply is maintained in the range 5.8 - 6.0. Grower One stated that if the pH is too high (> 6.2-6.5), it disrupts the availability of some nutrients such as iron and phosphorus. If the pH is too low (<5.8) root damage can occur, and root disease will occur more readily. In nutrient solution pH adjustment, nitric acid is added to the solution to reduce the pH, while potassium bicarbonate is used to increase it.

The EC of the nutrient solution is maintained at 2.2-3.5 mS/cm, depending on the growing season. Grower One stated that during a hot summer, the nutrient solution EC could be set up at a lower level (2.2-2.7 mS/cm) because in summer tomato plants' water consumption is high, and low EC nutrient solution makes it easier for the plants to absorb water.

However, the nutrient solution EC should never be set up too low (<1.8 mS/cm) otherwise it promotes the development of blossom end rot in the crop. During winter, the EC can be set up at a higher level of 3.0-3.5 mS/cm because tomato plants' water requirement is less due to lower temperatures and light levels.

Grower One also adjusts the nutrient solution's EC in response to the crop growing stage. At the beginning of the crop cycle, say during the vegetative growing stage, the nutrient solution EC supplied to the new slabs is set up at the lower end of the scale (EC=2.2) in order to encourage new plant root growth into the growing slabs. After the tomato crops mature to ensure good quality fruit towards the generative growing stage, the supplied nutrient solution EC is increased to a higher level (EC=3-3.5). In practice, the EC of the nutrient solution is adjusted by adding more or less fertiliser to the raw water and reused nutrient solution mix. The EC of the nutrient solution in the root zone can be manipulated by irrigation management, which will be discussed in the following section.

4.1.3.2 Nutrient Solution Supply

In Case Study One's greenhouses, the growing system is a media system. During production, there is generally a need for some over drainage out of the growing media. Grower One outlined several reasons for over draining, firstly, for EC control at the root zone, secondly, to refresh the nutrient ratios in the media, and thirdly, to ensure uniformity between slabs. In this section, the technical activities involved with Case Study One's irrigation management are described. Details include 4.1.3.2.1 *Daily Supply Strategies* and 4.1.3.2.2 *Supply Strategies in a Crop Cycle*.

4.1.3.2.1 Daily Supply Strategies

In Case Study One's greenhouses, the irrigation schedule is set up on a daily basis. The schedule is based on several indicators, which are the light levels in the greenhouse, the water content in the media slabs, the EC of the media slabs, and the EC of the nutrient

solution drainage. The following description is based on the irrigation management in one typical sunny summer day for mature tomato crops. The irrigation management strategies for other days during a year, and other crop growing stages, are similar – values for temperature, EC, water content, pH, light level, nutrient solution supply volume, and nutrient solution drainage volume will often change in differing circumstances.

No irrigation is supplied during the night. As a result, overnight the water content in the growing slabs decreases whilst the EC increases. During the daytime, after sunrise, increased light level leads to increased evaporation. As a result, the plants soon begin taking water up very quickly from the growing slabs. The water content in the growing slabs is continuously decreasing whilst the EC of the growing media rises.

The timing of the first irrigation during a day is considered very important by Grower One because it directly affects the tomato fruit's quality. Grower One explained that if the irrigation starts before the plant is actively transpiring, the plant will take up the water from osmotic pressure. The fruit act as a kind of reservoir for the plant, and as there is nowhere else for the water to go, it goes to the fruit, which expands beyond the limits to which it has grown. The result is that small fruit will develop splits, and large fruit will have surface microcracking. Therefore, the first irrigation should never start before the plants are actively transpiring. However, if the first irrigation starts too late, it will lead to a water shortage for the plants.

Grower One starts the first nutrient solution supply during a day when the light level achieves around $100\text{-}150\text{ J/cm}^2$. At this stage, the water content in the growing media slabs has usually reduced to 5%-10% less than the volume present at the last irrigation of the previous day, whilst the EC in the root zone is approximately 3.5 mS/cm.

There are two irrigation phases during a day. In the first irrigation phase, the main purpose is to increase water content in the growing slabs. Grower One sets up the irrigation at a lesser volume per time, more frequently. There no drainage from the slabs in this irrigation phase, therefore the water content in the slabs quickly increases.

“The more and smaller shots you do, the faster the increase in water content.”

The volume of the irrigation per time period is set up at around 100 ml per dripper¹¹ (equal to 200-220 ml/m²) for every 70-100 joule ratio¹². The irrigation frequency is around six cycles within two to three hours, depending on the light level. As there is no drainage during the first irrigation phase, the water content in the growing slabs is increased quickly whilst the EC of the growing media also rapidly increases.

After two to three hours, when the water content of the growing media has increased by around 10% and the EC of the growing media has risen to 4.5 mS/cm, Grower One starts the second irrigation phase of the day. The main purpose of the second irrigation phase is to reduce the EC level in the root zone, and maintain the water content of the slabs at a static level. This is because too high an EC level in the root zone forces the growing media to become too solid, which is not good for the root growth. A larger amount of the supplied solution can flush the slab so that the EC is reduced. In order to reduce the EC level in the root zone, Grower One sets up a larger irrigation volume per time period, but with reduced frequency in the second irrigation phase.

“If we don’t start getting some flushing through that slab to keep the EC down it will just sky rocket all day long.”...“It is larger shots less frequently which will allow the EC to drop away.”

Normally at the beginning of the second irrigation phase, the nutrient solution supply volume per time period is set up at around 200ml/dripper (equal to 450-500ml/m²) every 130-200 joule ratio. After the EC of the growing slabs has been reduced to around 3.5 mS/cm and is stabilised, the nutrient solution supply volume per time is reduced to 100 ml/dripper (200-220 ml/m²) every 130-200 joule ratio.

¹¹ For Case Study One, there are 2.0-2.2drippers/m² in the greenhouse, so 100ml/dripper=200-220ml/m²

¹² 1 joule ratio=1 J/cm²

The last irrigation supply during a day occurs a couple of hours before sunset. The exact irrigation stop time depends on the overnight dry down¹³ percentage in the slabs. Grower One states that the media slabs' dry down overnight is quite important because on the one hand, if the tomato plants are grown in a wet slab through the night, they are very likely to get root disease. On the other hand, the dry out action in the root zone actually promotes a bit of stress on the plants, which ensures the plants' pollen quality. In practice, Grower One controls the overnight dry down to an average 10%. The water content and EC are monitored by continuous meters in the growing slabs.

Appropriate water content and EC in the growing slabs for tomato crops vary in different seasons and crop growing stages. Therefore, the nutrient solution supply strategies vary during a crop cycle.

4.1.3.2.2 Supply Strategies in a Crop Cycle

In Case Study One the nutrient solution management strategies vary with the crop growing stage. Grower One stated that several key factors were related to nutrient solution supply management: crop stage, water content in the growing slabs, EC in the nutrient solution, EC in the root zone, and EC in the drainage.

The crop growing schedule in a 12-month year in Case Study One and some of the factors relevant to nutrient solution management are shown in Figure 4.1.2.

¹³ For this case, overnight dry down means the water content in the growing slab is reduced from the last irrigation in the afternoon to the first irrigation in the next morning.

Month	July	August	September	October	November	December	January	February	March	April	May	June
Crop stage	Vegetative phase (Young plants, no picking)		Generative phase (Mature plants, picking period)									
Water content in the slabs	100% before transplanting for new growing slabs, 75% after transplanting							55%			0%	
pH of the solution	5.8-6.0											
EC of the supply solution	2.2 mS/cm	3.3-3.5 mS/cm			2.2-2.7 mS/cm				3.3-3.5 mS/cm			
EC of the growing media	2.2 mS/cm	3.0-5.5 mS/cm								4.5-6.0 mS/cm	10.0 mS/cm	
Drainage	10-15% of supply volume		30-40% of supply volume				20-30% of supply volume			0%		

Clean up for 2 weeks

Figure 4.1.2 Case Study One cropping schedule and relevant nutrient solution management factors for a July planted crop.

Before new tomato plants are transplanted to the greenhouse, the new media slabs are continuously hydrated with nutrient solution for a couple of hours until their water content achieves 100%. Grower One stated that the hydrophilic nature of the growing media is significant for tomato plants’ root growth, especially for rooting volume, which will affect the tomato yield. For new growing media slabs, particularly rockwool, if they are not wet completely in the first irrigation they will never be thoroughly wet in their life cycle. Therefore, in this irrigation phase, to ensure that the new growing slabs’ water content increases quickly, Grower One takes care to see that no drainage comes out of the media slabs

After the new growing slabs’ water content has achieved 100%, new tomato plants are transplanted from the propagators to the slabs. From that point onwards until the following February, Grower One maintains the water content in the growing slabs at around 75% during the daytime. He considers that the water content of 75% in the growing slabs can not only match the tomato crops’ general water requirements but also it is a good level to

have as a buffer in the slabs throughout this growing period. Even occasionally when problems occur with the irrigation system, meaning that irrigation has to be stopped for a couple of hours to enable the equipment to be fixed, the tomato plants can survive without serious water shortage during these periods if the water content in the growing slabs is normally maintained at 75%.

“If you have something go wrong with your irrigation equipment, that is going to give you about three or four hours depending on the time of day to fix whatever the hell has gone wrong, and if you are less than 75% then all you are doing is eating into the amount of time you have up your sleeve. There is more potential for disaster.”

As February approaches, and the daylight hours become shorter than in early summer and the average temperature is dropping, the tomato crops' water consumption tends to be lower. Further, when the peak harvest period is approaching, reducing the water content in the growing slabs can prevent the tomato plants from absorbing too much water (which leads to the fruit becoming soft) to ensure that the quality of the fruit is maintained. Therefore, Grower One keeps the water content in the growing slabs at around 55% during the daytime in this period. At the end of the crop cycle, say from May to early June, Grower One reduces the water content in the growing slabs further, bringing it down to almost zero a couple of days before the last picking. He outlined two main reasons for reducing the water content in the growing slabs at the end of the crop cycle. The first one is to increase fruit quality. The second one is to reduce the weight of the growing media slabs. This is because the growing slabs are used for one crop cycle only. The used slabs have to be paid for by weight for disposal during the greenhouse clean up. A low water content in the slabs reduces the weight of the slabs, thus reducing disposal cost.

To ensure that the EC of the growing media is lower than that of the propagator, from which the new plants come, both the EC of the growing slabs and EC of the supply nutrient solution are maintained at around 2.2 mS/cm in the first 3-4 weeks after transplanting. Grower One stated that tomato plant roots absorb water more easily when

they are transplanted from a high EC root environment to a low EC root environment. To encourage the roots' growth into the new growing slabs, there is a need to maintain the EC in the new growing slabs at a lower level than that of the propagator at the beginning of the crop growing stage.

Three to four weeks after transplanting—say from late July to the end of April—as the tomato plants start flowering and setting fruit, to ensure that the tomato crops' nutrient requirements are met Grower One maintains the EC in the growing slabs at around 3-5.5 mS/cm. At this stage, the supply nutrient solution EC is 3.3-3.5 mS/cm in winter and 2.2-2.7 mS/cm in summer. He states that the EC in the growing slabs can not be too high during a hot summer because it is too tough for the plants to absorb water. After the mid April, as the temperatures are getting lower than those during the hot summer, and the end of the growing cycle is approaching, he maintains the EC in the slabs at a higher level which is around 4.5-6.0 mS/cm. In early June, around one week before the last picking, he considers that the daytime average EC in the growing slabs can be up to 10.0 mS/cm. From April to the end of the crop cycle, the supply nutrient solution EC is set up at 3.3-3.5 mS/cm.

The control of water content and EC in the growing slabs is manipulated by setting the irrigation schedule. A rough guideline used by Grower One is to set up the irrigation supply volume at 3 L/m² per day for every joule ratio. During the winter period, which is from early July to September (which is also the beginning of the cropping cycle) as the EC in the growing media is low, Grower One maintains the drainage percentage at around 10-15%. During the period from October to January, as it is hot summer, the temperature and light levels are quite high and the plants' water consumption is high. To ensure the EC in the growing slabs is not getting so high that conditions do not favour plant growth, Grower One allows more drainage in the nutrient solution supply, which is around 30-40%. After February, as the light level and the temperatures decrease, and the end of the crop cycle approaches, Grower One reduces the nutrient solution drainage percentage to 20-30%. Around 3-4 days before the end of the crop cycle, Grower One stops all the

nutrient solution supply to reduce the water content of the growing slabs. At this stage, there is no drainage coming out of the slabs.

4.1.4 Nutrient Solution Drainage Management

As the irrigation system in Case Study One is a recirculating system, the nutrient solution drainage is collected for reuse. Nutrient solution drainage management is described in the following section, including 4.1.4.1 *Collection and Storage*, 4.1.4.2 *Treatment and Reuse*.

4.1.4.1 Collection and Storage

In Case Study One's greenhouses, plastic trays are sited underneath the growing media slabs. The nutrient solution drainage comes out from the growing slabs, drains down onto the tray and is then collected in a pipe at the end of each row (Figure 4.1.3). The collected nutrient solution drainage then runs back to a central storage tank (Figure 4.1.4). The nutrient solution drainage in the central storage tank will flow to several smaller storage tanks through disinfection units. The nutrient solution drainage stored in those smaller tanks is ready for reuse in the next irrigation cycle.

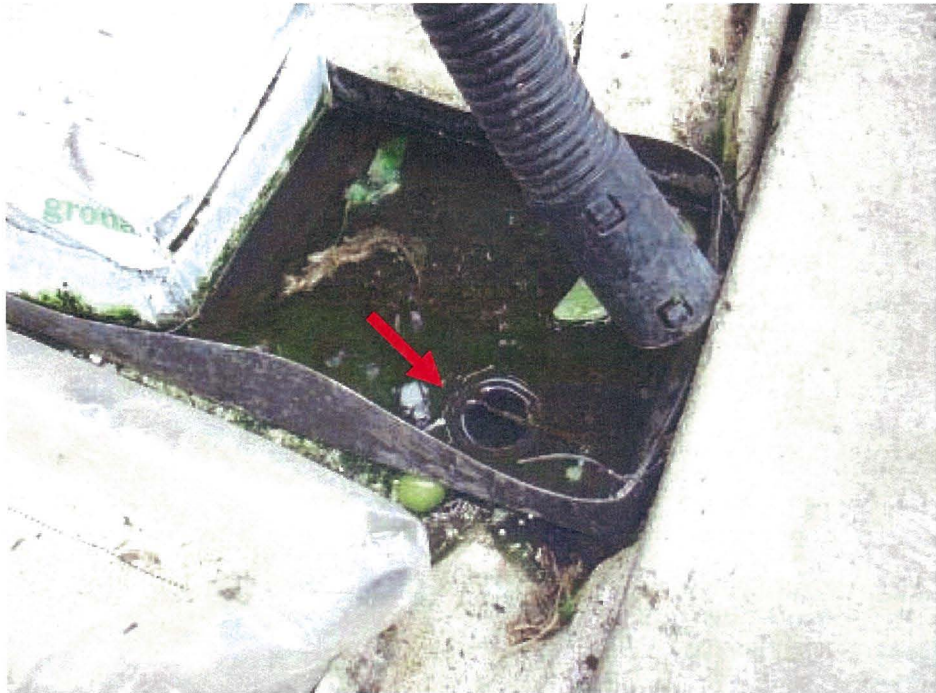


Figure 4.1.3 Surplus nutrient solution drains down onto the tray underneath the growing media slabs and then is collected in a pipe at the end of each row (red arrow)



Figure 4.1.4 Reused nutrient solution storage tanks (red arrow) and raw water storage tank (blue arrow).

4.1.4.2 Treatment and Reuse

The nutrient solution drainage is diluted by adding fresh water before it goes to the mixing tank to be blended with fresh nutrient solution. There are two main reasons for adding fresh water into the reused nutrient solution. The first one is to maintain the clarity of the nutrient solution drainage. This is because when the nutrient solution drainage is cloudy, it can not be treated efficiently by UV. Although the nutrient solution drainage has been filtered through a slow sand filter and a screen filter before it receives UV treatment, Grower One considers that one of the easiest ways to solve this problem is to add clean water to the nutrient solution drainage.

The second reason for adding fresh water is to reduce the nutrient solution's EC. Grower One explained that the EC of the nutrient solution drainage is normally higher than that of the supply nutrient solution because generally the plants take up more water than nutrients from the solution. Therefore, it has to be diluted before it is supplied to the crops again. The volume of the fresh water that is added is dependent upon the EC level of the nutrient solution drainage.

The volume of fresh water to be added to the nutrient solution drainage is also a function of the ratio of the reused solution to fresh nutrient solution. Grower One pointed out that in their recirculating system, the drainage storage tank is not big enough for the nutrient solution drainage to be stored for a long period. Therefore the nutrient solution drainage needs to be continually cycled through the system, otherwise the nutrient solution storage tank would overflow. He tries to maintain the amount of the reused nutrient solution drainage volume at approximately equal to the amount of the nutrient solution drainage volume coming out of the greenhouse. This is achieved by keeping a suitable ratio of the reused solution to fresh solution when they are blended in the mixing tank. During the period of the case study, Grower One used a ratio of reused solution and fresh solution at 1:3 because this ratio can ensure that the reused nutrient solution volume is generally equal to the nutrient solution drainage volume, thus keeping the whole recirculating system in a dynamic balance.

After the dilution, the reused nutrient solution goes to the mixing tank where it will be blended with fresh nutrient solution A and solution B, after which it flows back to supply the greenhouse crop.

In order to avoid the spread of root disease, it is necessary to maintain water and nutrient solution hygiene. In Case Study One's greenhouses, the irrigation water coming from the town water supply source is considered very clean and reliable, so it does not need any treatment. Fresh nutrient solution does not need any treatment either, because it is blended with sterilised irrigation water and pure fertiliser and contains no pathogens. Consequently, in Case Study One only rain water and nutrient solution drainage need to be treated.

Case Study One employs a slow sand filter and screen filter in combination with a UV unit (Figure 4.1.5) for irrigation water and drainage nutrient solution disinfection. The role of the slow sand filter and screen filter is to remove the dissolved solids in the raw water and the drainage nutrient solutions. Grower One explained that this is because the UV dose received by the pathogens in the water depends the clarity of the water. Grower One pointed out that filtration combined with UV treatment was considered reliable because in the past 3 years, no root disease had occurred in the greenhouses under this disinfection scenario. Further, in Case Study One's greenhouses, the technician who is maintaining the computer system and the irrigation system is also trained in maintaining the UV unit. UV treatment is considered to be the most convenient method for sterilisation on this property.

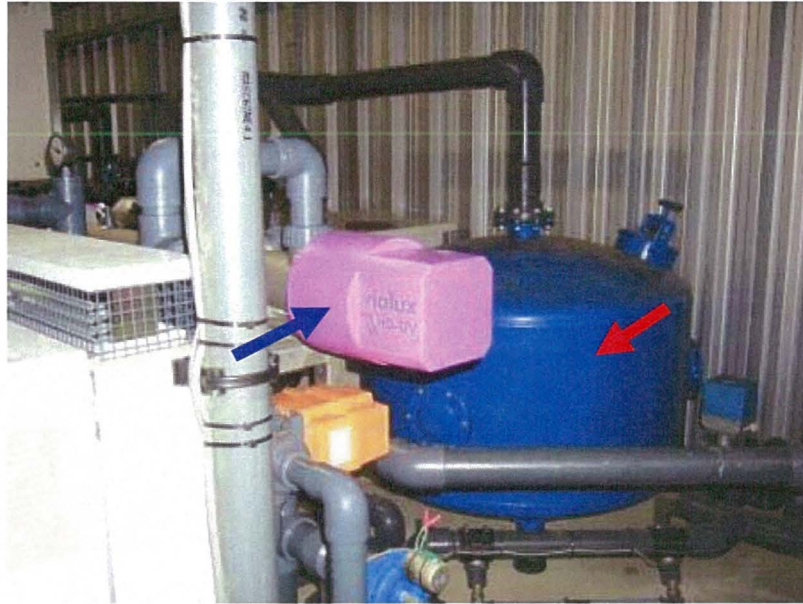


Figure 4.1.5 Nutrient solution mixing tank (red arrow) and UV treatment unit (blue arrow).

4.1.5 Nutrient Solution Disposal

In Case Study One, nutrient solution is disposed of infrequently. It happens only when a serious root disease has been identified. Grower One claimed that for the past three years, there had been no discharge at all from the growing system. There was no record for the nutrient solution volume per discharge. The estimated volume is 633 m³ per discharge (Appendix 2).

There is not specific nutrient solution disposal strategy used in Case Study One. Case Study One is located in an urban area, therefore there is not a lot of space available for waste nutrient solution release near the greenhouses. In Case Study One's hydroponic system, there is no storage facility designed for released nutrient solution storage. Consequently, when nutrient solution can not be reused, it is directly pumped out of the central nutrient solution storage tank then applied to a small area of lawn near the property (Figure 4.1.6).



Figure 4.1.6 Nutrient solution release site for Case Study One: small area of lawn.

Case Study One does nutrient solution drainage tests fortnightly (Appendix 3). Therefore, once nutrient solution discharge occurs, the released nutrient solution composition could be obtained based on the detailed laboratory analysis records. However, there was no record of the volume of each discharge. Also, there are no geographic information system (GIS) records, soil moisture records, rainfall record, or underground water depth records related to the release site used by Case Study One because no discharge has occurred during the last 3 years.

4.2 Case Study Report Two

Case Study Two is a small-scale, family-based greenhouse property. It is located in an upper North Island rural area. For this chapter, the nutrient solution management information was obtained by interviewing the owner, who is also the grower at the property. The interviewee will be referred to by the pseudonym “Grower Two” in the following section.

Grower Two has been involved in the greenhouse industry for more than 30 years. Previously, he produced tomatoes in a run-to-waste media system. Ten years ago he changed his growing system to a deep flow system (DFT) because he was told that producing tomatoes in a deep flow system can produce a higher yield and better quality fruit than could be obtained from a media growing system. After four to five years producing tomatoes in a deep flow system, he found that although the tomato yield and quality increased, the production cost increased also. At the end of the year he earned less money than before. Therefore, five years ago he shifted back to growing tomatoes in a media system.

The deep flow system Grower Two used was a recirculating system which included nutrient solution collection, storage, and disinfection facilities. Therefore, when Grower Two shifted back to the media growing system he started to recirculate the nutrient solution using the existing facilities. Compared to producing tomatoes in a run-to-waste media system, Grower Two saves fertiliser costs of \$2,000-\$2,500 per year by revising the nutrient solution. However, he stated that if he had not used a DFT before and had set up the nutrient solution reuse and disinfection facilities, he would have continued growing tomatoes in a run-to-waste system because it is easier to manage and set up.

Although Case Study Two’s growing system is a recirculating system, it has only basic control and monitoring equipment. Unlike Case Study One who releases the nutrient solution only in an emergency, Case Study Two releases nutrient solution regularly. There

are different nutrient solution management strategies in Case Study Two compared to Case Study One. Therefore, it was selected as one of the case studies.

4.2.1 Case Description

Case Study Two's greenhouses extend over 2,300 m². This comprises two houses; one a 1,000 m² glasshouse and the other a 1,300 m² plastic house. Both are over 30 year old "old style greenhouses" as the gutter height is approximately 2.0 to 3.0 metres. The growing system is a hydroponic media system.

The growing medium used in Case Study Two is pumice. Each tomato plant is grown in a PB12¹⁴ plastic bag containing approximately six litres of pumice with one self-compensating nozzle for irrigation supply. The crop density is 2.0 plants per square metre.

Grower Two does not collect the rainwater from the greenhouse roof because he has no rainwater collection and storage facilities. Also, Case Study Two is located in a rural area, where the town water supply is not accessible. Therefore, the only irrigation water source in Case Study Two is bore water from a 300-metre deep well. According to results of laboratory analysis, the sodium concentration of the bore water is 88mg/L, which is higher than the guideline level for hydroponic irrigation water¹⁵. In addition, the pH of the bore water is 9.2, which is also higher than the guideline level of hydroponic irrigation water¹⁶. However, Grower Two believes that the bore water quality is consistently high and good for irrigation use. Therefore he only adds acid to reduce the pH to 6.5-7.0 and does not adopt any other treatment before use. In practice, the acid is a blend of 3.3% phosphoric acid and 6.6% nitric acid.

The tomato crop cycle lasts seven months from January to late July. From August to December cucumbers are grown. This interview was conducted during the tomato

¹⁴ PB12=12 pint size plastic bag, 1 pint=0.568 liter.

¹⁵ The guideline sodium content in hydroponic irrigation water is 10-60 mg/l (Hill Laboratory)

¹⁶ The guideline pH for hydroponic irrigation water is 5.8-6.6 (Hill laboratory)

growing cycle. During production, the tomato crop's vertical growth is stopped by taking off the top shoot when the plants are about three metres high with 12-13 trusses. Tomato crop picking generally starts by the middle of March and finishes by the end of July. The average yield is 45,000-50,000kg per crop¹⁷, which is approximately equal to 19.5-21.7 kg/m² for seven months' production.

The pumice usually is reused for four to five years for both the tomato and the cucumber crops. After that the used pumice will be disposed of and reused in Grower Two's own paddocks as fertiliser and soil conditioner.

4.2.2 Hydroponic System

The hydroponic system in Case Study Two is a recirculating system. The flow of nutrient solution in Case Study Two's irrigation system is shown in Figure 4.2.1.

Bore water is stored in the raw water tank (1). Fresh solution A (2) and nutrient solution B (3) are stored in different fresh nutrient solution storage tanks, each having a capacity of 0.4 m³. Acid, which is used for raw water and nutrient solution pH adjustment, is stored in an acid tank (4). Acid is added to lower the pH before the bore water is used for irrigation. After pH adjustment irrigation water flows from the raw water tank to the mixing tank (5), which has a capacity of 10 m³. In the mixing tank, irrigation water, nutrient solution A, nutrient solution B, and the reused nutrient solution are blended together. The blended nutrient solution is pumped out of the mixing tank, supplied to the tomato crops in the greenhouses (6) through a self-compensating nozzle system after pH and EC have been adjusted. During production, the nutrient solution drainage is collected and stored in a drainage storage tank (7), which has a capacity 2.5 m³. The collected drainage solution can be recirculated to irrigate the greenhouse crops again, or be released out of the system. When the collected nutrient solution is to be recirculated, it is pumped out of the storage tank then flows to the mixing tank through a sand filter unit (8). The reused nutrient

¹⁷ For Case Study Two, one tomato crop cycle is seven months.

solution is blended with fresh water and the fresh nutrient solution and the cycle starts again. When the collected nutrient solution is not able to be recirculated, it is pumped out of the drainage storage tank and then released to the owner's paddocks (9) located nearby.

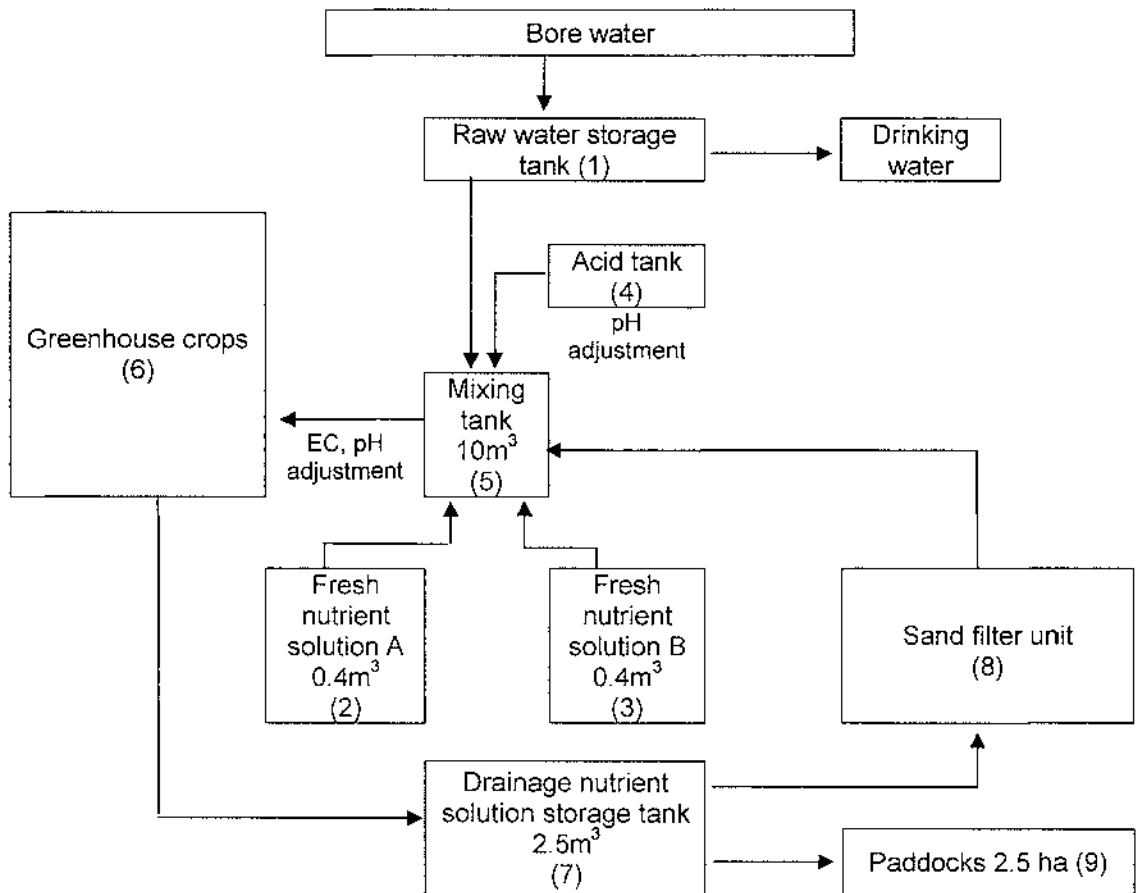


Figure 4.2.1 Case Study Two's nutrient solution flow diagram

In Case Study Two, there is one irrigation system to supply nutrient solution to the whole growing area. The process for nutrient solution management includes nutrient solution supply management, nutrient solution drainage management, and nutrient solution disposal. Management details will be presented in the next section.

4.2.3 Nutrient Solution Supply Management

In this section, the technical details of Case Study Two's nutrient solution management are presented. In section 4.2.3.1 *Formulation and Adjustment* details of the nutrient solution formulation and adjustment, which affect the composition of the supplied and drained nutrient solution, are provided. In section 4.2.3.2 *Nutrient Solution Supply* the nutrient solution supply management, which affects the nutrient solution supply and drainage volume, is described.

4.2.3.1 Formulation and Adjustment

In Case Study Two, the nutrient solution supply for the tomato crops is prepared by Grower Two. The fresh nutrient solution includes solution A and solution B. The grower uses the same recipe for both the glasshouse and the plastic house because the cropping schedule and the tomato variety in the two greenhouses are the same.

Grower Two formulates the nutrient solution based on a guideline for greenhouse tomatoes from computer software named "Nutron 2000". Six years ago, in order to find out whether the guideline suited the tomato variety he grew, the grower collected surplus nutrient solution drainage sent samples for laboratory analysis every two to three weeks over one crop's cycle. He then formulated his own nutrient solution for different crop growing stages. For the past six years, the nutrient solution management strategy used by Grower Two has basically been the same because during the period, he had changed neither the tomato variety nor the cropping schedule.

Grower Two stated that according his monitoring results, it was not necessary to adjust the nutrient solution composition too often because most of the time, the tomato crops' nutrient requirements did not change significantly. Only the potassium concentration needs to be considered carefully when the tomato plants start to flower and set fruit, in the seventh to eighth week after transplanting.

“Actually the whole thing is nearly the same, only the potassium as the plants get older, getting more potassium when they have a big fruit load on them.”

During production, Grower Two prepares 400 L of each of solutions A and B as a stock of fresh nutrient solution. After the stock nutrient solution has been used up, he will adjust the nutrient solution recipe and make up another quantity of solution for the next growing stage. Generally, 400 L of each of A and B solution can last two to three weeks in summer¹⁸ and four weeks in winter.

For the supplied nutrient solution, Grower Two maintains the pH at 5.8-6.2 and EC at 2.5-2.8 mS/cm. Grower Two varies the supply nutrient solution's EC from season to season and with different crop growing stages. Grower Two stated that in summer, when the temperature and light levels are high, tomato plants need more water than fertiliser. Therefore, he maintains the EC of the nutrient solution supply at 2.5 mS/cm. In winter, when the temperature and light levels are low, tomato plants need more fertiliser but less water. Therefore, he maintains the EC of the nutrient solution supply at a higher level, which is 2.8 mS/cm. In practice, Grower Two measures not only the EC of the nutrient solution supply but also the EC of the nutrient solution drainage. He adjusts the EC of the supply nutrient solution according to the EC of the nutrient solution drainage. He explained that if the EC of nutrient solution drainage was too high, it meant that the tomato plants had absorbed more water than nutrients. Therefore, the EC of the nutrient solution supply could be reduced. When the EC of the nutrient solution drainage was too low, it meant the tomato plants had absorbed more nutrients than water. Therefore, the EC of the nutrient solution supply could be increased to meet the plants' nutrient requirements. In practice, when the EC of nutrient solution drainage is lower than 4.0 mS/cm, Grower Two will increase the EC of the nutrient solution supply. In contrast, when the EC of the nutrient solution drainage is higher than 4.0 mS/cm, he will reduce the EC of the nutrient solution supply.

¹⁸ For Case Study Two, there is no exact definition of spring, summer, autumn and winter for seasons, but the grower roughly categorises the whole crop cycle from January to July into two seasons “summer” (January to April) and “winter” (May to July).

4.2.3.2 Nutrient Solution Supply

The growing system used by Case Study Two is a media system. During production, there is generally a need for some over drainage out of the growing media. In this section the technical activities involved with Case Study Two's irrigation management will be described. Details include 4.2.3.2.1 *Daily Supply Strategies* and 4.2.3.2.2 *Supply Strategies in a Crop Cycle*.

4.2.3.2.1 Daily Supply Strategies

In Case Study Two's greenhouses, the irrigation schedule is set up and adjusted irregularly. The schedule is based on several indicators, which are light levels in the greenhouse, nutrient solution supply and drainage volume. The following description is based on the irrigation management of mature tomato crops on a typical sunny summer day. The irrigation management strategies for other days during the year, and other crop growing stages are similar - but the relevant numbers refer to the nutrient solution supply volume, and nutrient solution drainage volume, which could be different.

The first irrigation of the day normally starts at 7:30-8:00 in the morning. Grower Two indicated that during a sunny day, the light level in the morning normally is lower than that in the afternoon. As such, in the morning Grower Two sets up the irrigation frequency at 45 minutes per cycle. In the afternoon however, while the light level is getting higher, the tomato plants require more water. Therefore, he sets up the irrigation frequency at every 30 minutes per cycle. The supply volume is 75-100mls per plant per time and 10-20 times daily. The daily supply volume and frequency depend on the weather, season, and the volume of the nutrient solution drainage. On a sunny day, since the light level is high and the plants' water consumption is high, the nutrient solution supply volume and frequency are higher than on a dull day. On a dull day, the plants' water consumption is lower hence the nutrient solution supply volume and frequency are lower than on a sunny

day. In summer, as the light levels are normally higher than in winter and the day time is longer than in winter, the tomato plants require more water. Therefore Grower Two sets up more irrigation supply volume per cycle, and dispenses it more frequently in summer than in winter. Further, if overnight greenhouse temperatures are too high he supplies nutrient solution once at midnight. He stated that supplying nutrient solution during hot summer nights can ensure the tomato plants' water uptake is sufficient for their requirements. In contrast, during winter, as the light levels are normally lower than in summer and day time is shorter than in summer, the tomato plants require less water. Therefore, Grower Two sets up less irrigation supply volume per cycle, and irrigates less frequently in winter than in summer. In winter no irrigations is supplied during night.

Nutrient solution drainage volume is another factor Grower Two considers when setting up the irrigation schedule. He measures the nutrient solution supply and drainage volume in a simple way. He selects a couple of plants in the greenhouses as samples. He lifts them up and puts a tray under each to collect the nutrient solution drainage. At the same time, he also puts an empty bottle beside each selected plant and puts a self-compensating nozzle in it to calculate the nutrient solution supply volume (Figure 4.2.2). He measures daily nutrient supply and drainage volume each week. If the drainage volume is more than 30% of the supply volume, he will reduce the nutrient solution supply volume. If the nutrient solution drainage volume is less than 25% of the supply volume, he will increase the nutrient solution supply volume.

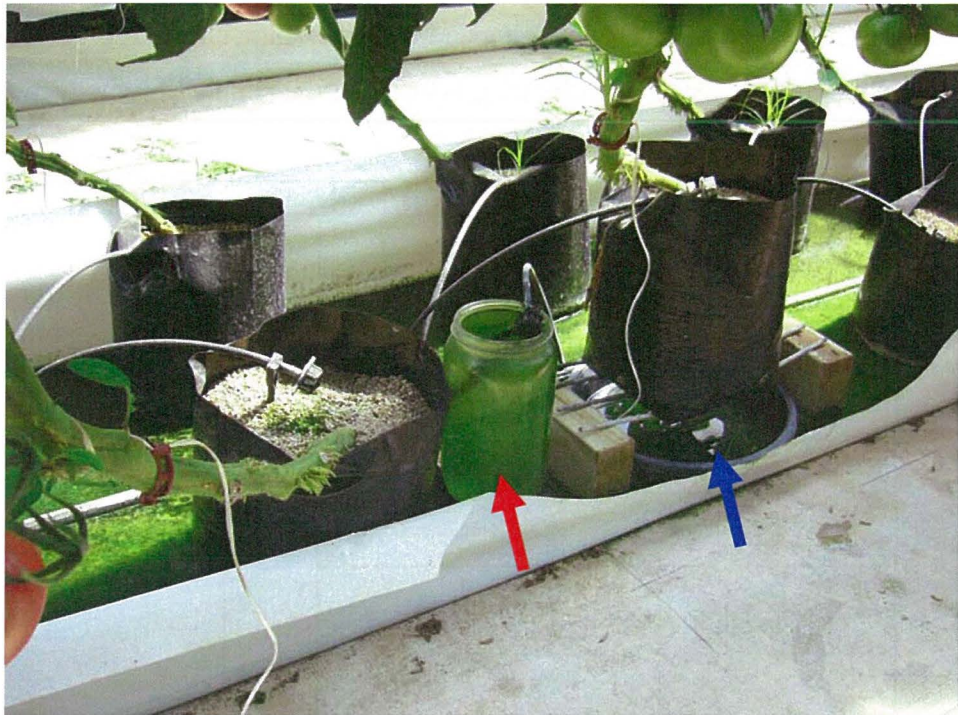


Figure 4.2.2 Glass bottle (red arrow) used for measuring supply volume and plastic tray (blue arrow) used for measuring drainage volume.

Besides the weather, season, and the nutrient solution drainage volume, the crop growing stage is considered as another key factor in irrigation management by Grower Two. Details of nutrient solution supply strategies during a crop cycle are described in the following section.

4.2.3.2.2 Supply Strategies in a Crop Cycle

Tomatoes are transplanted into the greenhouse at the beginning of January. During the first 7-8 weeks, the tomato plants are in the vegetative growing phase. Grower Two stated that the water requirement for the young plants in this phase is lower than it is for mature plants. During the first three to four weeks after transplanting, although it is January, the young plants' water and nutrient consumption is low because the plants are small. Therefore, Grower Two formulates the nutrient solution at a pH between 5.8-6.2, an EC level between 2.5~2.6 mS/cm, and sets the irrigation schedule at approximately 3 times a

day, 50-100 ml per cycle, depending on weather conditions. During this period, he maintains the drainage volume at 10-15% of the supply volume (Figure 4.2.3).

Month	January	February	March	April	May	June	July	August	September	October	November	December
Crop stage	Vegetative phase (young plants, no picking)		Generative phase (Mature plants, picking period)				Clean up 2 weeks	Cucumber crop cycle				Clean up 1 week
pH of the solution	5.8-6.2											
Nutrient solution EC	2.5~2.6 mS/cm	2.7~2.8 mS/cm										
Irrigation Frequency	3 time/day	10-20 time/day										
Irrigation Volume per Supply	50-100 ml/plant	75-100 ml/plant										
Drainage control	10-15%	25-30%										

Figure 4.2.3 Nutrient solution management in different crop growing stage in Case Study Two.

Around one month after transplanting, the tomato plants become more mature towards the generative growing phase and start flowering and setting fruit. At this stage, both water and nutrient consumption increase. Therefore, Grower Two increases the nutrient solution supply EC from 2.5~2.6 mS/cm to 2.7~2.8 mS/cm. Also he increases the irrigation frequency from three times per day to 10~20 times per day, the length of each watering is between 3 and 4 minutes and gives the plant approximately 75 to 100 ml of nutrient solution per time. At this stage, he maintains the drainage volume at 25-30% of the supply volume. And this irrigation schedule will last till the end of the crop cycle.

4.2.4 Nutrient Solution Drainage Management

As the irrigation system in Case Study Two is a recirculating system, the nutrient solution drainage is collected for recirculation. The nutrient solution drainage management technical practices are described in this section, including section 4.2.4.1 *Collection and Storage*, 4.2.4.2 *Treatment and Reuse*.

4.2.4.1 Collection and Storage

The greenhouses operated by Grower Two have a plastic tray underneath the growing bags of each row of the tomato crop (Figure 4.2.4). The nutrient solution drainage runs out of the growing bags and is collected in the tray. The collected drainage then flows into a pipe under the plastic tray through a hole in the tray and is collected in an underground storage tank.



Figure 4.2.4 Drainage nutrient solution is collected by a plastic tray placed underneath the growing bags with a hole (red arrow) in the middle of the tray for guiding the drainage.

The collected nutrient solution in the drainage storage tank is pumped out of the tank and passed through a sand filter. There is no storage facility at Case Study Two's property to store the untreated and treated nutrient solution separately. Therefore, after sand filter treatment the sterilised nutrient solution flows directly into the mixing tank where it will be blended with the fresh water and fresh nutrient solution.

4.2.4.2 Treatment and Reuse

There is one pH and one EC controller in the mixing tank. When the sterilised nutrient solution drainage flows into the mixing tank, it is blended with raw water and fresh nutrient solution A and B. The concentration of the mixed solution is adjusted by adding fresh water when the EC level is too high and by adding fertiliser when the EC level is too low.

The collected nutrient solution is normally recirculated for two to three weeks after which it is released out of the system regardless of conditions. Grower Two explained that this was because when the nutrient solution drainage had been reused for several cycles, salts build up. Even though the EC of the drainage is not too high, most of the ions in the solution are sodium and sulphate, which are not the nutrient elements the tomato plants require.

“After you reuse it starts building up (salts) and then you see it looks OK but there's only sulphate and sodium in it.”

Therefore, the old solution is unable to be reused and has to be replaced by fresh nutrient solution.

In order to avoid the spread of root disease, it is necessary to maintain water and nutrient solution hygiene. In Case Study Two's greenhouses, the irrigation water source from the

bore water is considered very clean by Grower Two, and does not need any disinfection before use. Grower Two stated that fresh nutrient solutions did not need any disinfection either because they were blended with clean irrigation water and pure fertiliser. The collected nutrient solution drainage, however, needs to be sterilised before being reused because it may carry root disease pathogens.

In Case Study Two, Grower Two uses a slow sand filter to treat the nutrient solution (Figure 4.2.5). Grower Two believes that the sand filter treatment can kill most of the harmful organisms in the solution. During the past five years Grower Two has used a slow sand filter to treat the nutrient solution drainage-and although there had been some of root disease in his greenhouses, the situation was no worse than that it had been in the run-to-waste growing system which he had used 10 years ago. Therefore, Grower Two considers that slow sand filter treatment is a reliable disinfection method.



Figure 4.2.5 Slow sand filter tank

4.2.5 Nutrient Solution Disposal

The nutrient solution discharge frequency is approximately every two to three weeks in summer and every four weeks in winter, depending on how long the stock of fresh nutrient solution lasts. When Grower Two starts to release the nutrient solution drainage, he will turn the switch between the drainage storage tank and the slow sand filter off, then put a hose onto the drainage storage tank and sprinkle the solution to his own paddocks located beside the greenhouses. No reused nutrient solution is allowed to feed back into the mixing tank during this period. Therefore, although the drainage storage tank's capacity is only 2.5 m³, it takes several days to totally empty the nutrient solution drainage from the system. The total volume per release is approximately 6 m³.

Case Study Two is located in a rural area. Grower Two has a 2.5 hectare paddock alongside his greenhouse operation. Although the surplus nutrient solution is worthless for greenhouse tomato growing, Grower Two considers it to be good fertiliser for growing grass in the paddock (Figure 4.2.6). Therefore, when Grower Two discharges the nutrient solution, he uses a mobile sprinkler to spread the solution over the whole paddock area as fertiliser. However, as the drainage solution storage tank's capacity is not big enough to store the nutrient solution for any period of time, Grower Two has no choice but to release the nutrient solution, no matter what the weather condition or ground conditions are.

Case Study Two has no record of the composition of the surplus nutrient solution from each release. Also, there is no other information kept about things such as a geographic information system (GIS) record, soil moisture status, or rainfall record related to the release site by Grower Two. The only information Grower Two provided is the estimated release volume each time.



Figure 4.2.6 Nutrient solution disposal area: paddocks.

4.3 Case Study Report Three

Case Study Three is a small-scale, family-based greenhouse property located in an upper North Island urban area. The nutrient solution management information in this chapter was obtained by interviewing one of the growers on the property. The interviewee will be referred to by the pseudonym “Grower Three” in the following section.

Grower Three has been involved in vegetable production for 27 years. At the beginning he grew outdoor vegetables, including a range of green crops for 7 years. Twenty years ago he bought a greenhouse property which had a 1,500 m² house. He started growing greenhouse tomatoes with this purchase and continues to do so till now. Over this period, he has bought two greenhouses and leased six other greenhouses. The total growing area is now 6,500 m².

One of the greenhouses Grower Three leased had a NFT recirculating growing system. However, during production, Grower Three found that it was very easy to get root disease problems when he grew tomatoes in that greenhouse. To reduce root disease risk, he stopped using NFT system and grew tomatoes in run-to-waste media systems in all greenhouses.

Case Study Three uses basic control and monitoring in his property. As the growing systems are run-to-waste systems, nutrient solution release occurs whenever drainage occurs. The nutrient solution management in this case study is quite different from those of Case Studies One and Two. In order to be able to compare the nutrient solution management strategies in different growing systems Case Study Three was selected as one of the case studies.

4.3.1 Case Description

The total greenhouse area in Case Study Three is 6,500 m². There are eight greenhouses which are all old style glasshouses of between 500 m² and 1,500 m². They are between 15 and 30 years old, and the gutter height is between 2.0 and 3.0 metres. Only tomatoes are produced in the greenhouses using a media system.

The growing medium used in Case Study Three is pumice. Tomato plants are grown in PB18¹⁹ bags filled with pumice. Each growing bag, which holds approximately 10 litres, has one tomato plant and one dripper for irrigation supply. The crop density is 2.5 plants per square metre.

The irrigation water source for Case Study Three is town water. Grower Three does not collect rainwater from the greenhouse roofs because he has no rain water collection and storage facilities. Also there is no bore in his greenhouses area. Therefore town water supply is the only irrigation water source. Grower Three never sends the town water sample to a laboratory for analysis because he believes that the quality of town water is consistently very high. Therefore, no treatment is applied before it is used for irrigation.

The property produces two crop cycles per year in each greenhouse. Grower Three germinates his own tomato plants. Normally it takes three to four weeks from germinating in the propagators to transplanting into the greenhouses. After transplanting, each crop cycle lasts approximately 6 months (24 weeks). After the tomato plants have been transplanted, there is no picking in the first 8-15 weeks (summer 8-10 weeks, winter 12-15 weeks). At this stage, the young tomato crops are basically in the vegetative growing phase. After flowering and fruit setting, the tomato crop matures and generative growth commences. Picking starts at the 9th to 16th week after transplanting and the picking period normally lasts 8-10 weeks, then the crop cycle finishes. Crop growth is controlled by removing the side shoots and the heads of the plants. Generally, tomato plants grown in Case Study Three's greenhouses have a single shoot with around 8-9 trusses of tomatoes.

¹⁹ PB18=18 pint size plastic bag, 1 pint=0.568 litre.

There are two tomato varieties grown in the property. The average annual yield is approximately 25 kg/m².

The cropping schedule varies in different greenhouses because Grower Three aims to have a year-round fresh tomato supply. He arranges the crop cycle randomly in each greenhouse to ensure he has tomatoes to supply the market each month.

The pumice is usually reused for three to four years. After three to four years the used pumice will be disposed of by being used in Grower Three's home garden, or his friend's garden as fertiliser and soil conditioner.

There is a greenhouse clean up, which lasts just two days, in each greenhouse between crop cycles. All the tomato plants from the previous cropping cycle are removed and new plants are transplanted into the old growing bags.

Beside the greenhouse clean up, there is an annual sterilisation after every second cropping cycle in each greenhouse. The greenhouse sterilisation normally lasts for two weeks including the five to six day clean up. After the greenhouse clean up, the greenhouse will be fogged using formalin and kept completely closed up for three to four days. Finally, the greenhouse is opened for two days to release the residual formalin and then it is ready for the next crop cycle.

4.3.2 Hydroponic System

The hydroponic system in Case Study Three is a run-to-waste system. The flow of nutrient solution in Case Study Three's irrigation system is illustrated in Figure 4.3.1.

Irrigation water from the town water supply is stored in the raw water storage tank (1), which has a capacity of approximately 10 m³. Fresh nutrient solutions A (2) and B (3) are stored in separate fresh nutrient solution storage drums. Each greenhouse has two 200 litre-sized storage drums to store solutions A and B because the nutrient solution

concentration for each house varies. The fresh nutrient solution A and B are diluted with fresh water to adjust the EC before they are blended. After blending, and pH adjustment, the solutions are supplied to the tomato crops (4) in the greenhouses using a drip system. During production, there is always some nutrient solution drainage from the growing media. In two of the greenhouses, the nutrient solution drainage is collected by a trough underneath the growing bags. The collected drainage is directly guided to open land (5) out of the greenhouse. In the other six greenhouses, however, the drainage nutrient solutions are directly drained into soil under the growing bags (6).

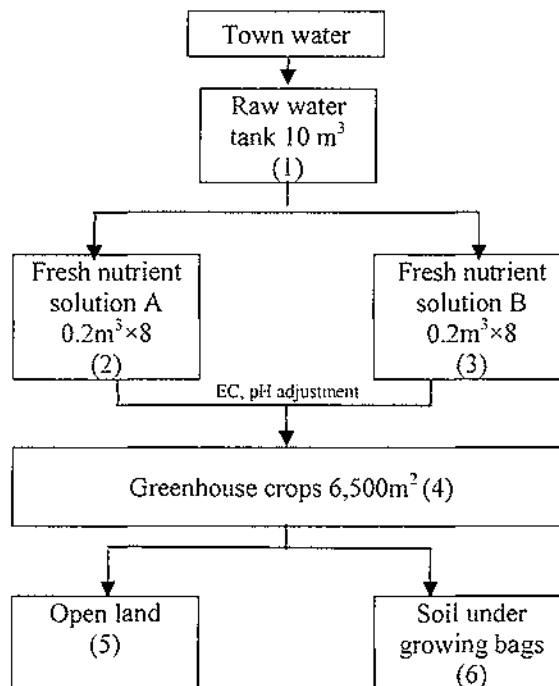


Figure 4.3.1 Nutrient solution flow diagram for Case Study Three

In Case Study Three, there are four irrigation systems, which cover areas of 500 m², 1500m², 1700 m², and 2800 m² respectively to supply nutrient solution to eight greenhouses. The reason for this is that the greenhouses are located in four separate sections. However, the nutrient solution management practices in the four systems are similar.

4.3.3 Nutrient Solution Supply Management

In this section, the technical details of Case Study Three's nutrient solution management are presented. In section *4.3.3.1 Formulation and Adjustment* the nutrient solution formulating details, which affect the composition of the supplied and drained nutrient solution, are provided. In section *4.3.3.2 Nutrient solution supply* the nutrient solution supply management details, which affect the nutrient solution supply and run-off volume, are described.

4.3.3.1 Formulation and Adjustment

When Grower Three first started growing greenhouse tomatoes, he asked a greenhouse consultant for an appropriate nutrient solution recipe. From this initial help Grower Three has developed his own approach. He uses the same recipe for each variety through the whole crop cycle during production and adjusts only the concentration, which is measured by EC, according to greenhouse environmental conditions and crop growing stages. He does not change the nutrient solution recipe often, only when he has serious problems with his tomato crops, such as extremely low yield or lower quality than usual. In these cases he sends a nutrient solution drainage sample to a laboratory for analysis. From the results of the analysis he then adjusts the nutrient solution formula as required. However, for the past five to six years, Grower Three had neither sent any sample to the laboratory to do analysis nor approached a greenhouse consultant about his nutrient solution management because he has been satisfied with his tomato yields and qualities.

Grower Three adjusts the supply nutrient solution EC in response to light level, plant growth stage, and the plant's performance. He stated that, in his experience, if the EC of the supply nutrient solution was too high at a high light level condition, the quality of the tomatoes declines, which presents as hard, small fruit. Since generally the light level is

high in summer²⁰ and low in winter, Grower Three maintains the supply nutrient solution EC at 2.5-2.7 mS/cm in summer and 3.0-3.5 mS/cm in winter (Figure 4.3.2).

		Geminating	Transplanted in greenhouses																							
Month			1st month				2nd month				3rd month				4th month				5th month				6th month			
Week		3 weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Summer	Crop growing stage	Gemination	Vegetative growing stage (Young plants, no picking)								Generative growing stage (Picking period)															
	Irrigation supply		Solution																Plain water							
	EC of the nutrient	2.5 mS/cm	0	2.5-2.7 mS/cm								0														
	Irrigation method	Hand watering	Through drip system																							
	Irrigation volume	Just keep wet	30-150 mls/plant																							
	Frequency of the irrigation supply	Once in a couple of days	18-20 times/day																							
	Percentage of the nutrient solution drainage	0%	0%								25%								0							
Winter	Crop growing stage	Gemination	Vegetative growing stage. Young plants, no picking								Generative growing stage. Picking period															
	Irrigation supply		Solution																Plain water							
	EC of the nutrient	3.0-3.5 mS/cm	0	3.0-3.5 mS/cm								2.5-2.7 mS/cm								0						
	Irrigation method	Hand watering	Through drip system																							
	Irrigation volume	Just keep wet	30-150 mls/plant																							
	Frequency of the irrigation supply (time/day)	Once in a couple of days	3-6 times/day																							
	Percentage of the nutrient solution drainage	0%	0%								25%								0							

Figure 4.3.2 Case Study Three's cropping schedule and relevant nutrient solution management factors.

²⁰ For Case Study Three, there is no exact definition of spring, summer, autumn and winter for seasons, but Grower Three distinguishes two growing seasons, summer (April to September) and winter (October to March).

Grower Three also adjusts the nutrient solution EC in response to the plant's growth stage. He uses the same concentration for feeding both young plants grown in propagators and plants grown in the greenhouse. He believes that even if the EC in the propagator is high, it does not stress the young plants very much since they are in the propagators for only three to four weeks, which he does not consider a long period.

"We use the same recipe... We just take it (nutrient solution) out of the tanks (to feed the young plants in the propagators)... It's not worthwhile making a separate solution for propagated plants because they are only in those pots for three to four weeks."

After the tomato plants have been transplanted into the greenhouse, in the first week Grower Three irrigates with just plain water to help the new plants' root establishment. After the new plants have been established, Grower Three starts to supply them with nutrient solution. During the vegetative growing stage, Grower Three has two approaches to nutrient solution EC adjustment. For the first approach, in the winter crop cycle, Grower Three maintains the supply nutrient solution EC at 3.0-3.5 mS/cm.

"I prefer generative plant even for young plants..."

He stated that although the tomato plants were in the vegetative growing stage, if the fertiliser supply was inadequate, the plants would present over-vegetative growth and then their following generative growth would be affected. Therefore, he prefers to supply the young plants with high concentration solution to avoid over-vegetative growth. However, this approach can not be used during summer. Grower Three explained that during summer, if the supply nutrient solution's EC is too high, salts build-up in the growing bags damages the tomato plant roots. Therefore, during summer, he uses a low EC solution (2.5-2.7 mS/cm)-and sometimes just plain water-to irrigate the young plants in the vegetative growing stage.

During the generative growing stage, Grower Three reduces the nutrient solution EC to 2.5-2.7 mS/cm. He stated that although the tomato plants were in the generative growing phase, if the EC of the nutrient solution was too high, the tomato plants would present overly generative growth and the tomato fruit would present small solid fruit.

“Some growers increase the EC at the end of the crop to get the quality but that’s what we used to do in the old days. We used to put a higher EC at the end of the crop, but I said it was a waste of money”.

At the end of the crop growing stage, say two weeks before the last picking. Grower Three stops nutrient solution supply and irrigates with just plain water. He stated that previously he used high EC solution to supply the tomato crops at the end of the crop cycle to try to improve the fruit quality-like many other greenhouse growers do-but found that by supplying plain water and maintaining minimal drainage at the same time, he can achieve the same goal. Therefore, he stopped supplying high concentration of nutrient solution to crops in this phase to save fertiliser cost.

Grower Three also adjusts the nutrient solution EC in response to the plant’s performance. He assesses plant performance by checking how the tomato plants look. He stated that if the tomato plants’ top shoots are formed very tight, it means that the EC of the supply nutrient solution is too high, or the water content in the growing bag is too low. Therefore, he reduces the supply nutrient solution EC, or increases the irrigation volume. If the top shoots present very weak, it means that the nutrient supply nutrient solution EC is too low, or the water content in the growing bag is too high. Therefore he will increase the supply nutrient solution EC, or reduce the irrigation volume in this situation.

Grower Three maintains the pH of the nutrient solution at the range of 5.8-6.1 for the whole crop cycle because this is the range the greenhouse consultant whom he used in the past suggested.

4.3.3.2 Nutrient Solution Supply

The growing system used by Case Study Three is a media system. During production, there is generally a need for some over drainage out of the growing media. In this section the technical activities involved with Case Study Three's irrigation management will be described. Details include *4.3.3.2.1 Daily Supply Strategies* and *4.3.3.2.2 Supply Strategies in a Crop Cycle*.

4.3.3.2.1 Daily Supply Strategies

In Case Study Tree's greenhouses, the irrigation schedule is set up and adjusted irregularly. The schedule is based on light levels in the greenhouse. The irrigation supply is controlled by a light sensor in each irrigation system which switches on and off automatically based on solar radiation measurements.

The way the light sensor works is to calculate the total amount of light energy, which is measured in joules. Grower Three sets up the irrigation supply when the light sensor collects every 250 joules of solar radiation. The first irrigation during a day will depend on when the light sensor collects 250 joules of solar radiation. The total irrigation time also depends on light level. For example during a sunny day the light sensor collects in total 2,500 joules of solar radiation, which means it triggers the irrigation ten times, then the total irrigation supply will be ten times per day. However, during a dull day, the light sensor collects only 1000 joules of solar radiation a day, which means it triggers the irrigation four times, then the total irrigation supply will be four times a day.

During the night, as the light sensor can not obtain solar radiation, there is no irrigation supply.

Grower Three stated that he has never reset the light sensor. He controls the irrigation volume by setting up different irrigation supply volumes per time based on the crop

growing stage. For young plants he sets up less volume per supply, while for mature plants he sets up more volume per supply because he believes that mature plants require more water and nutrient than young plants do. Technical activities on nutrient solution supply management in a crop cycle will be presented in the following section.

4.3.3.2.2 Supply Strategies in a Crop Cycle

Grower Three starts to supply nutrient solution to tomato plants when they are still growing in the propagators. He irrigates them once in a couple of days with limited volumes just to keep the propagators wet. Also, he waters by hand instead of using a drip system in this irrigation phase. No nutrient solution drainage occurs during this three weeks' irrigation phase (Figure 4.3.2).

After the tomato plants have been transplanted into the pumice bags in the greenhouses, Grower Three irrigates the new plants immediately to establish the roots. For the first one or two days, he usually uses a very low EC nutrient solution, sometimes just use plain water, to encourage the new plants' roots to establish into the pumice. Also, he uses manual watering instead of using the automatic control system because during this short period, the volume of the irrigation is limited so that it just keeps the pumice bags wet. No drainage occurs in this period.

One or two days after transplanting, the new plants' roots have been established. Grower Three then starts to supply the nutrient solution to the tomato plants through an automatic drip system. He sets up the irrigation schedule based on light levels and crop growth stages. During summer, as the light level is generally high, tomato plants absorb more water than nutrients in the solution. Therefore, more irrigation supply is needed. During winter, as the light level is generally low, tomato plants need less water and therefore less irrigation supply volume is needed. Grower Three sets up a nutrient solution supply schedule at a volume of 30-150 mls/plant per supply and 18-20 times/day in summer and approximately 5 times/day in winter.

“I prefer generative plant even for young plants. I always grow very, very dry plants.”

Grower Three maintains that no nutrient solution drainage occurred during the first three weeks after transplanting. He explained that during this period the tomato plants were in the vegetative growing stage. If the tomato plants are supplied with too much water or nutrient solution, they tend to over-vegetative growth. Therefore, he supplies less irrigation volume and ensures that no drainage occurs in this growing phase to avoid over-vegetative growth.

From the fourth week after transplanting Grower Three starts to supply more irrigation volume to ensure that there is some drainage. The aim of allowing some drainage is to reduce the EC in the growing bag. He determines the volume of the drainage by measuring the EC of the nutrient solution drainage. He stated that according to his own experience, the EC of the nutrient solution drainage should be 0.8-1.0 mS/cm higher than the EC of the supplied nutrient solution. If the EC of the nutrient solution drainage is more than 1.0 mS/cm higher than the EC of the supply nutrient solution, he increases the irrigation volume to allow more drainage to occur. If the EC of the nutrient solution drainage is less than 0.8 mS/cm higher than the EC of the supply nutrient solution, he reduces the irrigation volume to get less drainage. Generally, Grower Three sets up the irrigation volume at around 30-150 mls/plant per supply. During summer, he supplies 18-20 cycles per day while in winter just 3-6 cycles. Grower Three used to measure the EC of the supply and drainage solution by EC metre to determine whether he should adjust the irrigation schedule. However, most of the time he adjusts the irrigation schedule on the basis of his experience and does not measure anything. He does not measure the exact nutrient solution supply and drainage volume, but just estimates that the supply volume would be approximately an average of 3 litres per day per plant in summer, while it would be 0.75 litre in winter and the drainage would be approximately 25% of the supply volume. This irrigation phase will last until three weeks before the last picking.

Three weeks before the last picking, Grower Three stops supplying nutrient solution to the tomato crops. During this period, he just irrigates the plants with a small volume of plain water. He ensures that no drainage comes out of the growing bag to avoid a serious drop of the EC in the growing bag in this period to ensure that the quality of the fruit is maintained. This irrigation phase will last until the end of the crop cycle.

4.3.4 Nutrient Solution Disposal

As Case Study Three's irrigation system is a run-to-waste system, there are no nutrient solution drainage management activities in Case Study Three. There is no record of the nutrient solution drainage volume or frequency in Case Study Three. The annual nutrient solution drainage volume has been estimated at 912.0 m³ (Appendix 5). Grower Three stated that the nutrient solution drainage occurs only in a two-month period in each six-month crop cycle. As he arranges the planting time in each house randomly, it is assumed that in each month there are some tomato plants in the growing stage which need nutrient solution drainage. Therefore, the nutrient solution discharge in Case Study Three is daily.

There is not specific nutrient solution disposal strategy used in Case Study Three. Case Study Three is located in an urban area, so there are no grasslands or outdoor crops nearby the property. Therefore, the nutrient solution drainages are piped out of the greenhouses and are either released to the open land near the greenhouses (Figure 4.3.4) or drained directly into the soil under the growing bags.

There are eight greenhouses in Case Study Three. In two of them, the nutrient solution drainage is collected by a trough underneath the growing bags (Figure 4.3.3). As Case Study Three does not reuse the drained nutrient solution, the collected nutrient solution is not stored but is directly guided to the open land out of the greenhouse (Figure 4.3.4). In the other six greenhouses, the drained nutrient solutions soak directly into the soil under the growing bags.

No nutrient solution release records were provided by Grower Three because he claimed he had never measured any of the discharges and therefore did not have any information about them.



Figure 4.3.3 Nutrient solution drainage is collected by a plastic tray underneath the growing bags.



Figure 4.3.4 The nutrient solution drainage is guided to the open land out of the greenhouse through a pipe.

5. Cross-case Analysis

Cross-case analysis is used to identify patterns that occur across the cases investigated during the study (Eisenhardt, 1989). For this research, the case selection was based on a theoretical replication logic, which means that the cases were selected on the expectation that they would exhibit different results for predictable reasons (Yin, 2003). Therefore, one would expect to find different phenomena exhibited in each case. In this chapter, the results from the three case studies are compared and contrasted in relation to the nutrient solution management process. In section 5.1 the hydroponic systems used in the case studies are compared. In section 5.2 the nutrient solution supply management strategies used by the growers are compared. In section 5.3 the nutrient solution drainage management strategies in the case studies are compared. In section 5.4 nutrient solution disposal in the three case studies is compared. The reasons which lead to differences and similarities are identified.

5.1 Hydroponic Systems

The hydroponic systems operated in the three case studies are described in Table 5.1. Case Study One is a large-scale (40,000 m²) greenhouse enterprise. It uses a recirculating media system in modern glasshouses (5-6 years old) that have online computer control and monitoring systems. Case Study Two and Three, however, are small-scale (Case Study Two-2,300 m² and Case Study Three-6,500 m²) enterprises. Their greenhouses are old (15-30 years old) style with a range of cladding materials (plastic, glass) and they lack online computer control and monitoring systems. Case Study Two has a recirculating system and Case Study Three has a run-to-waste system.

Case Study One uses two types of growing media (coco-peat and rockwool) (Table 5.1). The media are used for only one crop cycle before being replaced because Case Study One aims to ensure that there are no root pathogens carried from one crop cycle to the next. In contrast, Case Study Two and Three use just one type of growing medium which is

pumice. Both Case Study Two and Three reuse the pumice for 4-5 years (Table 5.1) to reduce production costs. To prevent the carry over of root pathogens from one crop cycle to the next, both Case Study Two and Three sterilise the growing medium after each crop cycle.

Rainwater is the primary irrigation source for Case Study One (Table 5.1). The grower has a lined water storage pond which is used to collect and store rainwater from the greenhouse roof. The rainwater is supplemented with town water in summer if rainfall is inadequate. In contrast, neither Case Study Two nor Case Study Three has rainwater collection and storage facilities. Therefore they cannot use rainwater as their irrigation source. Case Study Two uses bore water as an irrigation water source, while Case Study Three uses town water (Table 5.1).

Table 5.1 A comparison of the hydroponic systems used by the three case studies

	Case Study One	Case Study Two	Case Study Three
Growing area (m ²)	40,000 m ²	2,300 m ²	6,500 m ²
Greenhouse type	Glasshouse	Glasshouse and plastic house	Glasshouses
Greenhouse age	5-6 years	30 years	15-30 years
Hydroponic system	Recirculating growing system with online computer control and monitoring	Recirculating growing system without computer online control and monitoring	Run-to-waste growing system without online computer control and monitoring
Growing media	Coco-peat, rockwool	Pumice	Pumice
Growing media reused	Not reused	Reused for 4-5 years	Reused for 4-5 years
Water source	Rainwater and town water	Bore water	Town water
Greenhouse gutter height (m)	4.5 m	2.0-3.0 m	2.0-3.0 m
Cropping schedule	One 12 month crop per year from July to June	One crop for 7 months from January to July	Two crops per 12 month period, 6 months per crop cycle
Yield	45-60 kg/m ² per year	19-21kg/m ² for 7 months crop	25 kg/m ² per year

Case Study One has high gutter height (4.5 m) greenhouses whereas Case Study Two and Three have low gutter height (2.0-3.0 m) greenhouses (Table 5.1). The greenhouse gutter height has implications for the way in which tomato crops are grown. Because of the restrictions imposed by the height of the glasshouse Case Study Two and Three cannot grow a tomato crop for the full 12 months. As a result, Case Study One uses a long-term crop cycle (12 months). Case Study Two and Three, however, use only a short-term crop cycle (6-7 months) for tomatoes. The yields achieved by the three case studies is a reflection of these different systems (Table 5.1). Case Study One, which has modern high technology greenhouses that grow one tomato crop over the 12-month period, produces the highest yield of 45-60 kg/m² per annum. In contrast, Case Study Two and Three, which use older technology greenhouses that grow short-term crops, produce much lower yields (19-21 kg/m² for a 7-month crop in Case Study One and 25kg/m² per annum in Case Study Two).

Table 5.2 presents the comparison of the facilities in the hydroponic systems used in the case studies. All these case studies have raw water storage tanks and fresh nutrient solution A & B tanks (Table 5.2). Case Study One and Two have mixing tanks which are used for fresh water, fresh nutrient solution, and reused nutrient solution blending. Case Study Three, however, does not have a mixing tank because the grower considers it unnecessary. In Case Study Three's irrigation system, the fresh nutrient solutions A and B are pumped directly into the pipes that supply the tomato crop.

Table 5. 2 A comparison of the facilities in each hydroponic system

	Case Study One	Case Study Two	Case Study Three
Raw water storage tank	√	√	√
Fresh nutrient solution storage tanks (A & B)	√	√	√
Mixing tank	√	√	
Nutrient solution drainage collection and storage facilities	√	√	
Disinfection facilities	√	√	
Sterilised nutrient solution storage facilities	√		

Because both Case Study One and Two operate recirculating systems, they must have nutrient solution drainage collection, storage, and disinfection facilities (Table 5.2). In contrast, Case Study Three operates a run-to-waste system and therefore does not need such facilities. Case Study One has the facilities to store the untreated nutrient solution drainage and treated nutrient solution drainage separately. They store the untreated nutrient solution drainage in the central nutrient solution storage tank and the sterilised nutrient solution drainage in reused nutrient solution storage tanks. Case Study Two, however, does not have the facility to separately store the untreated and treated nutrient solution drainage. This was because firstly, Grower Two indicated that to operate a recirculating growing system was not his initial wish. He just utilised some existing facilities from a DFT growing system which he had stopped using. Secondly, he stated that the investment costs of setting up more facilities-such as rainwater collection and storage facilities, treated nutrient solution storage facilities, UV units and so on-are prohibitive. Therefore, in Case Study Two the treated nutrient solution flows directly into the mixing tank for reuse (Table 5.2).

5.2 Nutrient Solution Supply Management

In this section, the nutrient solution management of the case studies is compared. In section 5.2.1 the nutrient solution formulation and adjustment activities of the case studies are compared. In section 5.2.2 the management of the case studies' nutrient solution supply is compared.

5.2.1 Formulation and Adjustment

All the case study growers formulate their own nutrient solutions. When formulating the nutrient solution, Case Study One must take into account the growing medium because they grow tomatoes in two types of growing medium. Both Case Study Two and Three use just one type of growing media and as such media type is not a concern in their

nutrient solution formulation. Grower One also takes into account tomato variety when formulating the nutrient solution because he grows four varieties of tomatoes that have different nutrient requirements. Because Case Study Two grows only one tomato variety this is not a factor he considers when formulating his nutrient solution recipe. Although Case Study Three grows two tomato varieties, he uses the same recipe for both varieties to simplify his nutrient solution management.

During production, the growers all adjust the nutrient solution recipe when necessary. Case Study One adjusts the nutrient solution recipe fortnightly on the basis of the composition of the nutrient solution drainage and the tomato plants' performance. Case Study Two and Three, however, adjust their nutrient solution recipe on the basis of plant performance. Case Study One analyses the nutrient solution drainage content at regular intervals. This process is not undertaken by Case Study Two and Three because firstly, they do not have the necessary monitoring equipment and secondly, they consider the cost of the analysis prohibitive. They also believe that as long as they continue to grow the same varieties of tomatoes in the same growing systems, the same nutrient solution management strategies can be used each year. As a result, only Case Study One uses regular laboratory analysis of the nutrient solution drainage for nutrient solution management. Case Study Two and Three rely on subjective assessment of plant performance.

The three case studies all adjust the nutrient solution concentration, which is measured by EC, in response to the different crop growing stages. For tomato plants in the vegetative growing stage (the period from transplanting to flowering and fruit set) Case Study One and Two supply low EC (2.2-2.7 mS/cm) nutrient solution because they consider that the fertiliser requirements of young plants are less than those of mature plants. Case Study Three, by contrast, uses relatively high EC (3.5 mS/cm) nutrient solution for tomato plants in the vegetative growing phase to avoid excessive vegetative growth, particularly in the winter crop cycle. For tomato plants in the generative growing phase (after flowering and fruit set), Case Study One and Two supply high EC (2.7-3.5 mS/cm) nutrient solution to the tomato plants to ensure high tomato fruit quality. In contrast, Case Study Three

supplies low EC nutrient solution (2.5-2.7 mS/cm) to the tomato plants to avoid excessive generative growth and save on fertiliser cost. The supply nutrient solution EC is considered important in all three cases because it affects not only tomato growth but also the salt build-up in the root zone, which in turn affects the irrigation supply and drainage volume. The nutrient solution supply details are discussed in the following section.

5.2.2 Nutrient Solution Supply

The irrigation schedules used by all three case studies are set up by the growers in response to the tomato plants' requirements and to control root zone salinity. Case Study One sets up and adjusts the irrigation schedule on a daily basis using the computer control and monitoring systems. The parameters Case Study One monitors through the computer system are light level, growing media moisture content, growing media EC, supply nutrient solution EC, and nutrient solution drainage EC. For Case Study Two and Three, nutrient solution supply depends on light level, crop growing stage, supply nutrient solution EC and nutrient solution drainage EC (Table 5.3).

Table 5.3 A comparison of the parameters measured by the growers

Factors	Case Study One	Case Study Two	Case Study Three
Light level	O*	S**	S
Growing media moisture	O		
Crop growing stage	S	S	S
Growing media EC	O		
Supply nutrient solution EC	O	O	O
Nutrient solution drainage EC	O	O	

* O=Objective

** S=Subjective

Case Study One has an advanced online computer control and monitoring system which allows him to measure light levels, growing media moisture content, growing media EC, supply and drainage nutrient EC. In contrast, Case Study Two and Three do not have computer control and monitoring systems. They measure light levels and crop growing stage subjectively. They do not measure the growing media moisture content and the EC

directly because they do not have the necessary instruments. Case Study Two measures the growing media EC indirectly by measuring the nutrient solution drainage EC using an EC meter. Case Study Three does not measure either the growing media EC or the nutrient solution drainage EC. He measures only the supply nutrient solution EC using an EC meter. He monitors the tomato plants' performance through visual observation, and this information to decide whether or not he should adjust the nutrient solution supply schedule.

The growers in all three cases all believe that the main purpose for allowing nutrient solution drainage to occur is to avoid salt build-up in the root zone. Under high light levels, tomato plants take up more water than fertiliser in the nutrient solution and this leads to a faster rate of salt build-up in the root zone than under lower light levels. Hence, all three growers increase irrigation supply and drainage volume to reduce salt build-up under high light levels.

Light levels are generally higher in summer and lower in winter, therefore season is an important consideration in the irrigation management of all three cases. They each increase nutrient solution supply and drainage volume in summer and reduce it in winter. The three cases also use lower nutrient solution concentrations under high light levels (during summer) than under low light levels (during winter) to avoid salt build-up in the root zone.

The three growers in the case studies all control the nutrient solution supply and drainage volume in response to crop growing stage (Figure 5.1). The three growers all believe that before young plants flower and set fruit, they generally require less water and nutrients. Therefore, at the beginning of the crop growing stage (vegetative growing stage), they all supply a low volume of nutrient solution, and allow less drainage volume to occur than in the generative growing stage. For Case Study One, drainage volume is maintained at 10% - 15% of the supply volume during the eight weeks after the young plants are transplanted. After that, Case Study One increases the drainage volume to 30% - 40% of the supply volume for the mature plants. However, at the end of the crop cycle, say two to three

months before the last picking, Case Study One will reduce the drainage volume to 20% - 30% of the supply volume. This is because during the peak harvest period, tomato plants need more fertiliser to maintain yield and quality. The root zone EC could be higher at this stage and therefore it requires less drainage volume to flush the growing media to reduce the EC. Several days before the last picking, Case Study One will stop nutrient solution supply to reduce the water content in the growing media. This reduces the weight of the media slab and hence its associated disposal cost because media slab disposal is calculated on the basis of weight. During this period, no drainage occurs (Figure 5.1).

		1st month	2nd month	3rd month	4th month	5th month	6th month	7th month	8th month	9th month	10th month	11th month	12th month
Case Study One	Growing stage	Vegetative growing stage			Generative growing stage								Clean up
	Drainage percentage of the supply volume	10-15%		30-40%						20-30%		0%	
Case Study Two	Growing stage	Vegetative growing stage		Generative growing stage			Clean up	Cucumber crop cycle					
	Drainage percentage of the supply volume	10-15%		25-30%									
Case Study Three		1st crop cycle					2nd crop cycle						
	Growing stage	Vegetative growing stage		Generative growing stage			Vegetative growing stage		Generative growing stage				
	Drainage percentage of the supply volume	0%		25%		0%	Clean up	0%		25%		0%	Clean up

Figure 5.1 A comparison of nutrient solution drainage at different crop growing stages

The nutrient solution supply strategies used by Case Study Two are similar to those used by Case Study One in the vegetative and generative growing stages. Case Study Two maintains the nutrient solution drainage volume at 10%-15% of the supply volume during the vegetative growing stage (the first 8 weeks after transplanting). The drainage volume will then be increased to 25%-30% of the supply volume in the tomato plants' generative growing stage, which starts approximately the 9th week after transplanting. However, Case Study Two does not reduce the nutrient solution supply and drainage volume at the end of the crop cycle as Case Study One does. This is because Case Study Two reuses the growing media and does not have to pay the growing media disposal cost by weight at the end of the crop cycle. Therefore, this nutrient solution supply scenario will be maintained till the end of the crop cycle, which is the 7th month after transplanting (Figure 5.1).

The nutrient solution supply strategies used by Grower Three are different from those used by Case Study One and Two. During the vegetative growing stage (the first 8-15 weeks after transplanting), the grower supplies a low volume of nutrient solution and ensures no drainage occurs (Figure 5.1). This is because the grower considers that this supply strategy can avoid excessive vegetative growth. When generative growth starts (after week 8-15), Case Study Three increases nutrient solution drainage volume to approximately 25% of the supply volume to reduce the root zone EC because by this point in time, the root zone EC has increased to relatively high levels. This irrigation scenario will last until the third week before the last picking. After that, Case Study Three stops the supply of nutrient solution to the plants and replaces it with plain water to save fertiliser. During this period, he maintains water delivery at a rate which will not allow drainage to occur to ensure that the EC in the root zone does not decrease to a level which will damage the plants (Figure 5.1).

5.3 Nutrient Solution Drainage Management

In this section, the nutrient solution drainage management of the case studies is compared. In section 5.3.1 the nutrient solution collection and storage in each case study is compared with the others. In section 5.3.2 the nutrient solution treatments and reuse strategies used by the case study growers are compared.

5.3.1 Collection and Storage

Both Case Study One and Two collect nutrient solution drainage in plastic trays underneath the growing media. Although Case Study Three collects nutrient solution drainage in two of the greenhouses, the collected solutions are not for reuse but are piped out directly for disposal because Grower Three operates a run-to-waste system. In Case Study One and Two, the collected solution is stored in nutrient solution storage tanks before reuse. The size of the central nutrient solution storage tank in Case Study One is

200 m³ for a 40,000 m² growing area. This grower also has four 20m³ storage tanks that store the treated nutrient solution drainage. In contrast, Case Study Two, with a growing area of 2,300 m², has only one storage tank, which is 2.5 m³, for untreated nutrient solution storage. Case Study Two does not have the storage facilities to store the treated nutrient solution because the investment cost to set up the facilities is considered high by the grower. Therefore, in Case Study Two the treated nutrient solution drainage flows directly to the mixing tank to blend with the fresh nutrient solution and water before reuse.

5.3.2 Treatment and Reuse

Both Case Study One and Two treat the collected nutrient solution drainage before reuse. Case Study One uses slow sand filters and screen filters combined with an UV unit to sterilise the nutrient solution drainage. By contrast, Case Study Two does not have an UV unit and screen filters because the cost of setting up such units was considered prohibitive. Instead, Case Study Two uses a slow sand filter to treat the nutrient solution drainage. Whereas Case Study One has not had a serious root disease outbreak over the past three years, Case Study Two has had occasional disease outbreaks. Both sterilising methods are considered reliable by the two case study growers. However, Case Study One has the better disease control result compared to Case Study Two because Case Study One uses more effective disinfection units to treat the nutrient solution drainage and irrigation water.

Once sterilised, the nutrient solution drainage is diluted with fresh water to reduce the EC before it is returned to the mixing tank to be blended with fresh nutrient solution. The primary source of irrigation water for Case Study One is rainwater. Town water is used as an additional water source when rainfall is inadequate over summer. An analysis of the two water sources showed that there are no sodium, chloride, or other ion problems in either the rainwater or the town water source. Because of this, Case Study One can reuse the nutrient solution continuously until a serious root disease has been identified. For Case Study Two, the irrigation water comes from a bore. According to the water analysis results, the sodium concentration of the bore water (88mg/L) was higher than the guidelines for irrigation water (10-60mg/L). As a result, sodium tends to accumulate in the

nutrient solution drainage in Case Study Two. To overcome this problem, Case Study Two must replace the nutrient solution drainage with fresh nutrient solution every two to four weeks.

5.4 Nutrient Solution Disposal

Case Study One releases nutrient solution into the environment only when a major root disease is detected within the system. Both the nutrient solution release frequency and volume are hard to predict. Therefore this type of nutrient solution release is classified as an *unplanned discharge*. In contrast, Case Study Two releases nutrient solution every two to four weeks at a volume of 6 m³ throughout the crop cycle. The nutrient solution release volume and frequency can easily be estimated. Therefore this type of nutrient solution release is classified as a *planned discharge*. Case Study Three, with its run-to-waste hydroponic system, releases nutrient solution out of the system whenever drainage occurs. As the daily release volume in Case Study Three is unpredictable, this type of nutrient solution release is also classified as *unplanned discharge*. A comparison of the nutrient solution release for the three case studies is presented in this section.

5.4.1 Volume and Frequency

No information about the nutrient solution release volume and frequency was provided by Case Study One. However, the volume has been estimated to be 633 m³ (Appendix 1). The frequency is assumed as once per three years (Table 5.4). For Case Study Two, the grower states that the nutrient solution release volume per time is approximately 6 m³. The release frequency is once every 2-4 weeks. The total nutrient solution release per crop cycle is estimated to be 54 m³ (Appendix 4). There is no information of the nutrient solution release volume and frequency provided by Case Study Three, but the volume has been estimated at an average of 12.2 m³ per day in summer and an average of 3.0 m³ per day in winter (Appendix 5). The annual discharge volume has been estimated to be 912 m³. Case Study One has the largest nutrient solution discharge volume because its growing

area is the largest of three cases. In contrast, Case Study Three has the most frequent rate of discharge because its growing system is a run-to-waste system (Table 5.4).

Table 5.4 Comparison of nutrient solution release volume and frequency

	Case Study One	Case Study Two	Case Study Three
Growing area (m ²)	40,000	2,300	6,500
Nutrient solution release volume (m ³)	633 m ³ per release	6 m ³ per release, 54 m ³ per 7 month crop cycle	Average 12.2 m ³ per day in summer and 3.0 m ³ in winter, 912.0 m ³ per year
Nutrient solution release frequency	Once per three year	Once every 2-4 weeks	Daily

5.4.2 Disposal

Only Case Study One regularly records the nutrient solution drainage composition. Grower One undertakes a detailed nutrient solution drainage analysis every fortnight because he adjusts the supply nutrient solution recipe based on the results of this analysis. Case Study Two undertakes this analysis on an annual basis only because the grower considers the cost prohibitive. In contrast, Case Study Three has not undertaken any form of nutrient solution drainage analysis for five to six years because he considers it expensive and unnecessary.

The nitrogen concentration of the drainage nutrient solution differs across case studies because the growers use different nutrient solution recipes. They also adjust the nutrient solution concentration in response to the tomato growing stage. Therefore the nitrogen concentrations of the drainage nutrient solution vary in each set of laboratory analysis results. Based on data provided by the case study growers, the nitrogen concentration of the drainage nutrient solution is between 133-491 mg/l. Assuming that the average nitrogen concentration in the drainage nutrient solution is 300 mg/l, the total amount of nitrogen is estimated to be approximately 189.9 kg per release for Case Study One (Table 5.5). For Case Study Two, the total amount of nitrogen is estimated to be approximately

1.8 kg per release and for a 7-month crop cycle the nitrogen discharge volume is approximately 16.8 kg (Table 5.5). Case Study Three is estimated to release approximately 3.6 kg of nitrogen per day in summer and 0.72 kg of nitrogen per day in winter. This grower is producing 2 crop cycles per year. The amount of nitrogen Case Study Three releases on an annual basis is estimated at approximately 274.2 kg (Table 5.5).

Table 5.5 Comparison of nitrogen release for case studies

	Case Study One	Case Study Two	Case Study Three
Nitrogen release (when N concentration=300mg/l)	189.9 kg per release	1.8 kg per release 16.2 kg per crop cycle	Average 3.6 kg per day in summer, 0.9 kg per day in winter 274.2kg per year
Require release site area (ha) (When application rate is 30kgN/ha every 3 weeks)	6.33 ha per release	0.06 ha	2.52 ha in summer. 0.63 ha in winter.
Available release site area (ha)	Not available	2.5	Not available
Tomatoes produced per year (1000 kg)	2,400 (At a yield 60kg/m ²)	48 (At a yield 21kg/m ²)	162 (At a yield 25kg/m ²)
Nitrogen discharge per 1000kg of tomatoes produced (kg N / 1000 kg Tomato)	0.03 (Assuming discharge once per three years)	0.33	1.69

Assuming that the maximum nitrogen application rate that can be applied to the release site is 30 kg N/ha every three weeks²¹. For Case Study One, assuming its nutrient solution discharge frequency is once per three years, an area of 6.33 ha is needed to release the 189.9 kg of nitrogen at a rate of 30 kg N/ha (Appendix 2) (Table 5.5). However, Case Study One is located in an urban area. There is limited area available for nutrient solution release near the greenhouse. Therefore, Case Study One does not select a suitable release

²¹ Application rate 30 kg N/ha every three weeks is the maximum limit suggested in the COP (Lewthwaite et al., 2006).

site before nutrient solution disposal. And also due to insufficient nutrient solution storage capacity, Case Study One cannot store the nutrient solution for a long period. Therefore the released nutrient solution is piped directly out onto a small area of lawn beside the greenhouses when there is a need.

It is assumed that for Case Study Two, the nutrient solution release occurs once every three weeks in summer and once every four weeks in winter. Therefore an area of 0.06 hectare is needed for nitrogen release in summer and winter (Appendix 4) (Table 5.5). The grower owns 2.5 hectares of pasture beside the greenhouses and this is used as his nutrient solution release site. Therefore, the size of Case Study Two's release site is sufficient to cope with the amount of nitrogen discharge per release. Also, as Case Study Two reuses the nutrient solution as fertiliser, he uses a sprinkler to spread the nutrient solution to the pasture. However, due to insufficient nutrient solution storage capacity, Case Study Two cannot store the nutrient solution for a long period. The nutrient solution has to be released whenever there is a need.

For Case Study Three, the nutrient solution is released on a daily basis. The grower needs a release area of 0.12 ha/day in summer and 0.03 ha/day in winter. For a three-weeks period (21 days), the grower requires a release area of 2.52 hectares in summer and 0.63 hectare in winter for nutrient solution release (Table 5.5). However, Case Study Three is located in an urban area and he does not have a suitable release site on the property. Therefore, Case Study Three does not select a suitable release site before nutrient solution disposal. As Case Study Three does not have any nutrient solution storage facilities, the nutrient solution cannot be stored before disposal. Therefore the nutrient solution is either piped onto a small area of open land beside the greenhouses, or drains directly into the soil under the growing bags.

The release area data show that only Case Study Two has a suitable release site and sufficient area for nutrient solution release. Therefore it is likely to meet the requirements in the COP. Neither Case Study One nor Case Study Three has a suitable release site and sufficient area for nutrient solution release because they are located in urban areas.

Therefore, they are considered unlikely to meet the requirements in the COP. None of the case study growers stores the nutrient solution until the release site is in suitable condition for disposal. Therefore, none of them meets the requirements in the COP.

Case Study One produces 2,400,000 kg tomatoes per year. Assuming that the nutrient solution discharge frequency is once every three years, he can release 0.03 kg nitrogen into the environment per 1000 kg of tomatoes produced (Table 5.5). Case Study Two produces 48,000 kg of tomatoes every seven months. In each crop cycle, Case Study Two releases 16.2 kg nitrogen into the environment. Therefore, he is estimated to release 0.33 kg nitrogen per 1000 kg of tomatoes produced. This is 11 times the amount released by Case Study One. Case Study Three produces 162,000 tomatoes per year. He releases 274.2 kg nitrogen into the environment per year for two crop cycles. Therefore, he is estimated to release 1.69 kg nitrogen per 1000 kg of tomatoes produced. This is 56 times the amount released by Case Study One and 5 times the amount released by Case Study Two.

These data show that recirculating systems such as Case Study One and Two provide an advantage over run-to-waste systems such as Case Study Three in terms of nitrogen released per 1000 kg of tomatoes produced. For recirculating growing systems water quality is critical in minimising the nutrient solution release frequency, hence minimising the nitrogen release volume. Case Study Two uses bore water which contains a high concentration of sodium as an irrigation water source. Therefore, although the grower is operating a recirculating system, he needs to release 11 times of the nitrogen per 1000 kg tomatoes produced compared to Case Study One. Provided that disease does not present a problem, if Case Study Two uses high quality irrigation water which contains a lesser concentration of ions, its nutrient solution release frequency and the nitrogen release volume per 1000 kg tomatoes produced will be significantly reduced.

Although Case Study One has nutrient solution drainage analysis results, the results are used for nutrient solution supply management. The case study growers in this research do not calculate the exact volume of each release and do not conduct a risk assessment before

they release nutrient solution because these activities have never been matters of concern to them. None of the case studies has full detailed nutrient release information records.

6. Discussion

This section compares the results from the case studies to the literature and the industry's code of practice (COP) produced by Lewthwaite et al. (2006). Those areas that were identified from the literature as being important in minimising the environmental impact of liquid waste (nutrient solution) produced by greenhouses' tomato production system are discussed. These include:

- (1) adopting efficient hydroponic systems (Van Os, 1994; Tognoni et al., 1998; Van Os, 1999)
- (2) efficiently managing the nutrient solution (Donnan, 1994; Bell & Marchant, 1998; Magen, 1999; Savvas & Adamidis, 1999; Kempkes & Stanghellini, 2003), and
- (3) adopting suitable strategies to dispose of the nutrient solution (Lewthwaite et al., 2006).

The comparison of the case study results with the literature will be structured in this way. Section 6.1 compares the hydroponic systems in the case studies and the literature. Section 6.2 compares the nutrient solution supply management practices in the case studies and the suggestions in the literature. Section 6.3 compares the nutrient solution drainage management practices in the case studies and the literature. Section 6.4 compares the nutrient solution disposal practices in the case studies and the guidelines in the literature.

6.1 Hydroponic Systems

For greenhouse tomato production the primary means of minimising the amount of nutrient solution that is released into the environment is to adopt a recirculating hydroponic system (Van Os, 1994; Tognoni et al., 1998; Van Os, 1999). This is because recirculating hydroponic systems collect and reuse the nutrient solution rather than discharging it directly into the environment. Therefore, the frequency of discharge from such systems is far less than it is from run-to-waste systems (Magen, 1999; Van Os, 1999; Bugbee, 2004; Dhakal et al., 2005). In New Zealand, the COP has been developed to assist greenhouse growers to minimise nutrient solution release environmental impacts in

New Zealand conditions. It also suggests that the nutrient solution discharge frequency can be reduced by using a well-designed hydroponic system. A recirculating system is preferred (Lewthwaite *et al.*, 2006). These recommendations were supported by the case study results. Case Study One and Two operate recirculating systems, therefore their nutrient solution discharge frequency and amount of nitrogen released per 1000 kg of tomatoes produced was far less than those of Case Study Three, which operates a run-to-waste system.

The literature suggests that modern greenhouses with on-line computer control and monitoring systems generally provide better production conditions and as a result produce higher yields (Mason, 1990; Smith, 1999; Giacomelli, 2004). Similar results were found with the case studies. Case Study One has modern style, high gutter height glasshouses with on-line computer control and monitoring systems. This produces much higher yields than do Case Studies Two and Three, which operate older style, low gutter height greenhouses without on-line computer control or monitoring systems.

Although the literature (Tognoni *et al.*, 1998; Schnitzler, 2004) and the COP (Lewthwaite *et al.*, 2006) recommend the use of recirculating systems to minimise the environmental impacts of nutrient solution release, the case study results suggest that small-scale greenhouse growers may prefer to operate run-to-waste systems. The primary reason given by Case Study Three, a small-scale grower, for not operating a recirculating system was the high capital cost of such systems, a point made by Romer (1993). Several authors (Savvas & Adamidis, 1999; Savvas, 2002; Schnitzler, 2004) have also pointed out that small-scale growers tend not to adopt recirculating systems because the management of such systems requires advanced technologies, particularly in the areas of root disease control and nutrient imbalance adjustment. The case study results support this viewpoint. In this research, although Case Study Two, a small-scale grower, was operating a recirculating growing system during the case study period, it was not the grower's first choice. Grower Two previously used a DFT²² system which he gave up on. However, he has continued to use the nutrient reuse and disinfection facilities from this system in his

²² DFT is a media-less recirculating growing system which contains nutrient solution disinfection facilities.

existing recirculating operation. Similarly, Case Study Three operated a leased greenhouse with a recirculating system, but he changed it to a run-to-waste system because he found it was too difficult to manage the nutrient solution and maintain disease control. Several authors (Schwarz, Schroder, & Kuchenbuch, 1996; Savvas & Manos, 1999; Van Os & Postma, 2000) have pointed out that the main disadvantages of recirculating growing systems are their high investment cost, high risk of root disease, and requirement for advanced technologies. Therefore, although recirculating systems appear to be the most suitable growing systems for minimising the environmental impact of nutrient solution release, the case study results suggest that small-scale growers may not adopt such systems because of, firstly, the high capital cost and secondly, the difficulties associated with managing the nutrient solution and disease control in such systems.

6.2 Nutrient Solution Supply Management

After the systems design, the second area that influences nutrient solution drainage volume and the nutrient solution discharge frequency is nutrient solution supply management (Nichols, 1989; Mason, 1990; Romer, 1993; Valente et al., 1998; Peet, 2004b). Nutrient solution drainage volume can be reduced by setting up a suitable nutrient solution supply schedule (Valente et al., 1998; Peet, 2004b). Similarly, both salinity and disease control are critical if growers want to reduce the frequency of nutrient solution discharge (Savvas & Adamidis, 1999; Van Os & Benoit, 1999). The key factors affecting nutrient solution supply schedules include growing media type (Mason, 1990; Romer, 1993), greenhouse environment (Nichols, 1989; Valente et al., 1998; Peet, 2004b), and the crop growing stage (Wilkerson, 1998; Peet, 2004a). This section compares the case study growers' practices and the suggestions in the literature.

A growing medium's water holding capacity is one of the key factors that affects the irrigation schedule (Uronen, 1995; Tuzel et al., 2001a; Peet, 2004b). The COP also suggests that the nutrient solution drainage percentage will vary depending on type of growing media used by the grower (Lewthwaite et al., 2006). Although Case Study One uses two different growing media, the irrigation management practices for each is similar

because their water holding capacity is similar. Both Case Studies Two and Three use only one type of growing medium. As such, the case study growers manage nutrient solution supply more with regard to the greenhouse environment and the crop growing stage rather than the media type.

Temperature and solar radiation are two key factors that also affect the irrigation schedule (Nichols, 1989; Valente et al., 1998; Jones, 2004; Peet, 2004b). Irrigation supply and drainage volume are generally high in high temperature or light conditions because tomato plants require more water and salinity problems are more likely occur in such conditions (Nichols, 1989; Valente et al., 1998; Jones, 2004; Peet, 2004b). Similar recommendations are provided by the COP (Lewthwaite et al., 2006). The case study results show that the growers also follow these practices. During summer when temperature and light levels are high, all the case study growers supply greater irrigation volumes and allow a larger percentage of drainage volume. In contrast, during winter when temperature and light levels are low, the irrigation volumes and percentage of drainage volume are reduced. The growers set up daily irrigation schedules based on light levels. Similarly, during the daytime when light levels are high, the growers supply nutrient solution to the crops and allow a certain amount of drainage. In contrast, during night-time, the growers reduce, or stop the irrigation supply and therefore little-or no-drainage occurs over this period.

It is generally recommended that when tomato crops are in the vegetative growing stage, the nutrient solution supply EC should be set lower than when the crops are in the generative growing stage (Jones, 2004; Peet, 2004b). Several authors (Bar-Yosef, 1988; Hao et al., 2000; Dorais, Papadopoulos, Athanasios, Gosselin P, & Andre, 2001; Li et al., 2001) reported that increasing nutrient solution supply EC increases not only tomato fruit quality but also yield when the tomato crop is in the generative growing phase. When Case Studies One and Two formulate and adjust their nutrient solutions they follow these practices. They use a low EC nutrient solution for tomato plants during the vegetative growing phase and increase the nutrient solution EC during the generative growing phase. Grower One and Two's nutrient supply arrangement followed those supported by the literature. They supply low EC nutrient solution to their tomato crops in the vegetative

growing phase and maintain less drainage volume. However, they increase the drainage volume when they supply high EC nutrient solution to crops to avoid the salt build-up in the root zone.

Case Studies One and Two supply less irrigation volume and maintain less drainage volume during the tomato crops' vegetative growing stage and increase these during the generative growing stage. At the end of the crop cycle, Case Study One reduces the nutrient solution drainage volume to maintain a higher EC level in the root zone to ensure fruit quality. This Grower also stops irrigation a couple of days before the last picking to lower the water content in the growing slabs to reduce the disposal cost. Case Study Two does not reduce nutrient solution supply and drainage volume at the end of the crop cycle; instead, he supplies higher EC solution to maintain higher EC in the root zone. The irrigation strategies of both growers are similar to those advocated in the literature (Wilkerson, 1998; Peet, 2004b).

In contrast, Case Study Three uses a relatively high EC nutrient solution for tomato plants in the vegetative growing phase and then reduces the nutrient solution EC in the generative growing phase. Furthermore, he supplies plain water instead of nutrient solution for the three weeks that end the crop cycle. When Grower Three supplies plain water to tomato crops, he said that no drainage occurs. The grower uses these practices to limit overly vegetative growth during the vegetative growing phase and to reduce fertiliser costs at the end of the crop cycle. Grower Three stated that his nutrient solution strategy did produce high quality tomatoes. However, this nutrient solution strategy was not reported in the literature. Yield data have shown that this grower produced the lowest yield amongst the case studies.

6.3 Nutrient Solution Drainage management

Because Case Study One and Two use recirculating systems, the nutrient solution drainage from their greenhouses is collected and stored for reuse. In contrast, Case Study Three, which has a run-to-waste system, uses a combination of open and guided drainage systems. In Case Study Three's open drainage system nutrient solution drainage is not collected, but drains directly into the soil under the greenhouses. In contrast, with the guided drainage system the nutrient solution drainage from Case Study Three's greenhouses is collected. However, unlike the typical guided drainage system described by Tognoni et al. (1998) in which the collected nutrient solution is stored before disposal, the collected nutrient solution in Case Study Three is piped directly onto the open land beside the greenhouses. In this section, the nutrient solution drainage management practices of the three case studies are compared with the literature and the COP. Firstly, the nutrient solution collection and storage practices are compared in section 6.3.1, secondly, the nutrient solution drainage treatment and reuse are compared in section 6.3.2.

6.3.1 Collection and Storage

To avoid environmental pollution from nutrient solution discharge, the COP states that irrespective of the hydroponic system used, the drained nutrient solution from a greenhouse must be collected and stored for reuse or disposal (Lewthwaite et al., 2006). In terms of the drained nutrient solution storage capacity, Bell and Marchant (1998) argue that sufficient capacity should be provided to prevent any pollution due to overflow. The COP states that if the nutrient solution is stored for disposal, it should be stored until the release site is in a suitable condition for release (Lewthwaite et al., 2006). In New Zealand, due to the weather conditions, drained nutrient solution is generally required to be stored for up to two weeks in summer and four months in winter (Lewthwaite et al., 2006). Table 6.1 compares the actual storage capacity of the three case studies with the requirements as specified in the COP (Lewthwaite et al., 2006). This shows that none of the three case studies has sufficient storage capacity as specified by the COP. The reasons given by the case study growers for not having adequate storage capacity were the limited space for

storage tanks on site (Case Studies One and Three) and the high capital cost of such storage facilities (Case Studies Two and Three).

Table 6.1 A comparison of the required nutrient solution storage capacity and the actual storage capacity in the case studies.

	Required summer storage capacity (m ³)	Required winter storage capacity (m ³)	Actual storage capacity (m ³)
Case Study One	696.3	696.3	280
Case Study Two	6.6	19.8	2
Case Study Three	187.9	198	0

6.3.2 Treatment and Reuse

In recirculating growing systems the salinity of the nutrient solution drainage and root disease pathogens are two key factors that affect the nutrient solution reuse cycle and hence the nutrient solution discharge frequency (Magen, 1999). To minimise salinity problems and avoid the accumulation of unwanted ions in the nutrient solution, the use of high quality irrigation water is considered important in hydroponic growing systems (Donnan, 1994; Jensen, 1997; Magen, 1999; Jones, 2004).

Case Study One follows the practices advocated in the literature and uses rainwater, which contains few ions, as his primary irrigation water source. This grower also treats the rainwater using slow sand filter, screen filter, and UV unit to remove potential pathogens before irrigation use. As these practices minimise the likelihood of either unwanted ions or root disease pathogens accumulating in the nutrient solution, the nutrient solution can be continuously recirculated. Therefore, the nutrient solution release frequency in Case Study One is the lowest amongst the three case studies. Also Case Study One releases the lowest volume of nitrogen into the environment per 1000 kg of tomatoes produced amongst the case studies. Case Study Two provides an interesting contrast to Case Study One. Although Case Study Two also uses a recirculating system, the grower has to replace the

nutrient solution every 2-4 weeks because he uses water from a bore that contains a high concentration of sodium (88 mg/l)²³. Donnan (1994) suggested that growers should use water treatments to remove unwanted ions when the water's ion concentration is too high. Although Case Study Two's irrigation water has high sodium concentration problem, the grower did not consider using an ion removal treatment because of the high investment cost. Therefore, because of the sodium accumulation the drained nutrient solution cannot be reused indefinitely. Grower Two must replace the nutrient solution every 2-4 weeks. As a result, Case Study Two releases 11 times the volume of nitrogen into the environment per 1000 kg of tomatoes produced than Case Study One releases.

As stated previously, the incidence of root disease is a major problem for recirculating growing systems such as those used by Case Study One and Two and it is one of the key factors that influences the nutrient solution release frequency (Donnan, 1994; Jensen, 1997; Magen, 1999; Jones, 2004). Therefore, root disease pathogen control in this type of system directly affects the nutrient solution reuse cycle and the release frequency (Bell & Marchant, 1998; Van Os, 1999). Case Study One sterilises the irrigation water and nutrient solution drainage using UV units in combination with slow sand filters and screen filters. This grower has reported no serious root disease during the past three years. As a result, Case Study One has been able to continuously reuse the nutrient solution without any release in this period. Several authors (Runia, 1995; Runia, Michielsen, Kuik, & Os, 1997; Nederhoff, 2000a, 2000b; Lewthwaite et al., 2006) have suggested that this level of performance is possible with good root disease pathogen control. However, because of the high capital cost of UV units Case Study Two grower used a less expensive slow sand filter to remove pathogens from the nutrient solution. The grower stated that he had not had a serious root disease outbreak since he had begun using the slow sand filter to treat the drainage solution in his recirculating system. Van Os et al. (1998) suggested that slow sand filters provide adequate disinfection for recirculating systems. Therefore, small-scale growers, particularly those who need to replace the solution at regular intervals may not need to purchase expensive sterilising units such as UV units because replacing nutrient solution regularly reduces the chance of disease build-up.

²³ The guideline sodium content in hydroponic irrigation water is 10-60 mg/l (Hill Laboratory).

Schnitzler (2004) stated that using pathogen-free growing media can significantly reduce root disease risk. All three case study growers followed this practice. Case Study One achieved a pathogen-free goal by replacing the growing media after each crop cycle. Case Studies Two and Three, however, achieved the same end point by sterilising the growing media after each crop cycle. These small-scale growers preferred to reuse the growing media for several crop cycles to reduce the production costs, particularly because with their low-technology greenhouses these growers had a production cycle of only 6-7 months. A similar suggestion was also given by Gunnlaugsson and Adalsteinsson (1995).

Case Study Three operates a run-to-waste system. This grower does not sterilise either his irrigation water or his nutrient solution. Not surprisingly, the grower stated that root disease and unwanted ion accumulation are not problems in his greenhouses. This result supports the view of several authors that run-to-waste systems have simple requirements in terms of technological inputs and have a relatively low risk in relation to root disease (Mason, 1990; Donnan, 1994; Smith, 1999; Jones, 2004).

6.4 Nutrient Solution Disposal

In order to reduce the environmental impacts of the nutrient solution, its disposal is considered a critical component of nutrient solution management. The released nutrient solution contains large proportions of nutrients (Bell & Marchant, 1998; Tognoni et al., 1998; RIRDC, 2001; White, 2002). On the one hand, it is a potential source of pollution to the environment. On the other hand, the released nutrient solution could be reused as fertiliser (Bell & Marchant, 1998; RIRDC, 2001). Principles in the literature state that nutrient solution disposal should avoid nitrogen leaching to the ground water and surface water (McLaren & Cameron, 1996; Cornforth, 1998). The COP (Lewthwaite et al., 2006) gives very detailed guidelines on nutrient solution disposal. The recommended nutrient solution disposal practices include: releasing the nutrient solution to land rather than to water; releasing the nutrient solution to a site where the solution can be reused as fertiliser for plant growth; releasing the nutrient solution when the site is in suitable condition to

avoid nitrogen leaching; and recording the detailed release information (Lewthwaite et al., 2006). Growers One and Three, who are located in an urban area, have very limited space for nutrient solution release, therefore they just pipe the released solution out to a small area of lawn (Case Study One), the open land (Case Study Three) beside their greenhouses, or directly drain it to the soil under the growing bags (Case Study Three). These practices cannot meet the requirements in the COP. Case Study Two uses sprinklers, which is a recommended method in the COP, to spread the nutrient solution to pasture as fertiliser. Although this is a practice suggested in the COP, the grower has to conduct the activity whenever there is a need because he has insufficient drained nutrient solution storage capacity. None of the case study growers records nutrient solution release information because they have not been required to do so prior to the time when the case study was on taken. Therefore, as far as the nutrient solution disposal stage is concerned, none of the case study growers adhere to the guidelines suggested by the COP.

7. Conclusion

The main objective of this research was to investigate the nutrient solution management and disposal practices of New Zealand hydroponic greenhouse tomato growers and, further to investigate whether or not these practises meet to the guidelines set out in *The Management of Nutrient Solutions Released from Greenhouses: A Code of Practice* (COP). This objective was met by addressing the following objectives:

- (1) to review the literature on nutrient solution management in hydroponic systems
- (2) to investigate the current practices that New Zealand commercial greenhouse tomato growers use in nutrient solution management and disposal
- (3) to compare the commercial greenhouse growers' nutrient solution management and disposal activities with the suggestions in the literature and requirements in the *The Management of Nutrient Solutions Released from Greenhouses: A Code of Practice* (COP) and then to estimate whether or not the commercial greenhouse growers' practices meet the requirements in the COP.

A multiple-case study research design was selected as the method to achieve the research objectives. This chapter presents the main finding from the study and the implications of the research for greenhouse tomato growers and greenhouse industry. The research method used in the study is evaluated and the areas for future research are identified.

7.1 Main findings

The findings of this research show that none of the case study growers fully met the guidelines given in the COP. In the entire nutrient solution management process (which includes nutrient solution supply management, nutrient solution drainage management, and nutrient solution disposal), the weaknesses are mainly in the nutrient solution drainage management section and the nutrient solution disposal section. The case study growers lack nutrient solution disposal strategies. Main issues are: (1). Urban growers lack suitable

release sites for their nutrient solution disposal (2). None of the case study growers releases the nutrient solution only when the release site is in a suitable condition (3). None of the case study growers records the nutrient solution release information. The reasons why the case study growers cannot meet the requirements in the COP include: the case study growers did not consider the environmental impact of their nutrient solution discharge. Urban area greenhouses such as Case Study One and Three have limited nutrient solution disposal area near their greenhouses. Therefore, they do not select a suitable release site to release the nutrient solution. Also, none of the case studies has sufficient nutrient solution storage capacity to store the released nutrient solution for long periods of time as required in the COP. Therefore, they cannot release the nutrient solution when the release site is in a suitable condition. They have to conduct the release whenever there is a need. None of the case study growers fully recorded the nutrient solution release information during the case study period because they had been never required to do that in the past.

Although none of the case studies fully meet the guidelines given by the COP, recirculating growers Case Studies One and Two manage nutrient solution better than the run-to-waste grower, Case Study Three, in terms of reducing the nutrient solution discharge frequency. They release less volume of nitrogen into the environment per 1000 kg of tomato produced in their recirculating growing systems. Therefore their performance is considered to be close to the guidelines in the COP. Run-to-waste growers discharge the nutrient solution more frequently than do the recirculating growers. They release a greater volume of nitrogen into the environment per 1000 kg of tomato produced. Therefore they are considered unlikely to be able to adhere to the guidelines in the COP because of their system design.

The research results further show that high-technology large-scale greenhouses (such as Case Study One) discharge nutrient solution less frequently than low-technology small-scale greenhouses (such as Case Studies Two and Three). The reasons were that high-technology greenhouses have modern high stud height greenhouses with advanced control and monitoring systems. These advanced growing systems ensure that the growers

manage nutrient solution and control root disease efficiently. Therefore they produce long-term tomato crops and obtain the highest yield amongst the case studies. Also, they release the lowest nitrogen volume to the environment per 1000 kg of tomato produced. Low-technology small-scale greenhouse growers have low stud height old style greenhouses. They lack advanced control and monitoring systems because they do not have sufficient capital invested. Therefore they produce short-term tomato crops and obtain lower yields than do high-technology greenhouse growers. As they cannot manage nutrient solution and control root disease efficiently, they release a greater volume of nitrogen to the environment per 1000 kg of tomato produced.

The research results show that only recirculating greenhouses such as Case Studies One and Two consider nutrient solution drainage management in their nutrient solution management process. Run-to-waste greenhouses such as Case Study Three do not consider this at all. Therefore, the run-to-waste grower in this case study does not have a drained nutrient solution storage facility. Although recirculating growers have drained nutrient solution collection and storage facilities, none of the case study properties had sufficient nutrient solution storage capacity as required in the COP at the time this study was undertaken. The reasons include: lack of investment capital, lack of space, and the fact that the growers have never been worried about storing the nutrient solution for such a long period as the COP requires. To avoid collected drained nutrient solution overflow due to insufficient storage capacity, high-technology large-scale growers continuously reuse nutrient solution and release it only when there is an emergency. Low-technology small-scale greenhouse growers cannot continuously reuse nutrient solution because they lack high technologies, and advanced control and monitoring systems. Therefore, they have to release nutrient solution regularly (recirculating systems), or daily (run-to-waste systems).

According to the results, nutrient solution discharge for recirculating systems can be classified into two types in the three case studies: unplanned discharge such as occur in Case Study One, and planned discharge such as occur in Case Study Two. Unplanned discharges occur only in an emergency, such as when a serious uncontrolled root disease

outbreak is found. Planned discharges happen regularly during production due to the ion accumulation or nutrient solution replacement after crop cycles. Unplanned discharge is more likely to happen in high-technology large-scale greenhouses because in these greenhouses nutrient solution is continuously reused and does not have to be released regularly. However, because high-technology greenhouses such as Case Study One have a large growing area, when the nutrient solution needs to be released, the volume is large and the potential nitrogen leaching risk is high.

7.2 Implications of the Findings

The findings of the case study show that at the current stage, none of the case study growers fully adhere to the guidelines suggested in the COP. The implications of this finding are: on the greenhouse growers' side, they need to consider the environmental impacts of their nutrient solution discharge in the future. To comply with the RMA and regional plans, greenhouse growers should follow the guidelines given by the COP to improve their performance. On the industry side, the development of suitable guidelines to assist greenhouse growers to better comply with the RMA and regional plans needs to be considered.

The findings show that one of the main reasons the case study growers failed to meet the requirements in the COP was that the case study greenhouses either did not have drained nutrient solution storage facilities (Case Study Three) or have insufficient storage capacity (Case Studies One and Two) to store the drained nutrient solution for a long period as required in the COP. The implications of this finding are: on the growers' side, they need to set up facilities for drained nutrient solution collection and storage; otherwise they cannot meet the requirements in the COP. Although the best option to meet the requirements in the COP would be to set up sufficient nutrient solution storage capacity, some properties might have limited space or limited investment capital to achieve the goal. For these growers, removal of nutrient solution out of the system to an authorised disposal site (for example the sewerage system), may be the alternative disposal option. On the industry's side, the provision of nutrient solution collection and storage facilities should

be considered more carefully in the future. Without these facilities growers will simply fail to meet the COP requirements and will fail to meet regional authority regulations.

Another significant reason why the case study greenhouse growers failed to meet the requirements in the COP was that the urban area growers have no suitable nutrient solution release site near their greenhouses. The implications of this finding are: on the growers' side, although it is not possible to change the location of existing greenhouse properties, for future growers who intend to run a new greenhouse, the ability to access a nutrient solution disposal area needs to be considered. On the industry's side, assisting greenhouse growers to discharge nutrient solution in a sustainable manner needs to be highlighted. Traditionally, in greenhouse location selection the emphasis has been on the possibility and convenience of market access, obtaining sufficient solar radiation, and obtaining high quality irrigation water. However, in the future the possibility and convenience of accessing a nutrient solution disposal site also needs to be considered.

The findings from this research show that recirculating hydroponic systems readily meet the requirements suggested in the COP. In contrast, run-to-waste hydroponic systems are considered a long way from this standard. The implications of this finding are: on the growers' side, run-to-waste growers need to change their hydroponic system to a recirculating growing system in the future. Otherwise they will not adhere to the guidelines in the COP or comply with the RMA and regional plans. This will be a capital-intensive process. Small-scale family-based greenhouse enterprises may find this impossible. Hence, low-technology small-scale greenhouses may not survive in the future. On the industry side, the development of high-technology large-scale greenhouses with disposal sites nearby is considered the trend for the industry in the future.

7.3 Assessment of the Method

The method used in this research was a multiple case study. There were three greenhouse properties involved in this research. The case study process followed the theory given by

Yin (2003), which includes “case study define and design”, “case study data prepare, collect, and analyse” and “case study analyse and conclude”.

The literature on nutrient solution management in hydroponic growing systems was reviewed. The literature review included two sections, which were general theories on nutrient solution management and specific guidelines related to natural resources management in New Zealand. The literature review was used to develop the research framework. The cases were selected and the data collection protocol was developed based on the literature review. The data collection methods included semi-structured interviews, field observations, and collecting documentations of related materials. The data obtained from the case studies were qualitatively analysed. The data analysis process included within-case analysis, cross-case analysis, and comparison of the case study results to the literature. Lastly, the findings from the case studies were analysed and discussed.

The case study method allowed the researcher to obtain in-depth understanding about the nutrient solution management practices used by New Zealand greenhouse growers. In order to compare the technical activities adopted by greenhouse growers in different production conditions, a multiple case study was preferred to a single case study in this research. Three cases, with varying property size, system design, irrigation water source, growing media type, crop cycle, and location, were selected in this research because the researcher believed that these cases represent the current greenhouse industry in New Zealand. The results presented distinct management activities used by the growers in the cases. Therefore, the multiple case study design was found appropriate for doing this research.

Semi-structured interviews provided detailed information about greenhouse growers' nutrient solution management practices. Tape-recording the interview conversations was very important because it ensured that the researcher did not miss any detailed information provided by the interviewees. Field observations were conducted in each interview and it was found very useful in confirming the information described by the interviewees. Archival records provided by the greenhouse growers were found very helpful on

corroborating and adding details to the interview results. Therefore, the methods used during data collection were appropriate.

The qualitative data analysis process advocated by Dey (1993) was found suitable for this research. The tape records obtained from each interview were transcribed into a written document. Within-case analysis was conducted through data description, classification, and connection. After that the results obtained from each case study were compared with each other and then compared to the literature review.

Although there was literature on nutrient solution management in hydroponic growing systems, little information was given on how commercial greenhouse growers minimise nutrient solution discharge environmental impacts in New Zealand. Therefore, limited guidance was obtained from the literature about the main problem domains which are the focus of this research. For the entire nutrient solution management process (which includes nutrient solution supply management, nutrient solution drainage management, and nutrient solution disposal) the management strategies used by the case study growers were focussed on the nutrient solution supply and nutrient solution drainage management sections. Limited information was obtained in the nutrient solution disposal section from the interviewees. Therefore, most of the analyses were based on the estimated numbers; the validity of the results needs to be tested in the future.

7.4 Future Research

For this research, three cases were selected, including one high-technology large-scale recirculating greenhouse which is located in an urban area, one low-technology small-scale recirculating greenhouse which is located in a rural area, and one run-to-waste greenhouse which is located in an urban area. The selected case studies were all located in the North Island of New Zealand. In future, a broad survey around the whole country should be conducted to ascertain whether or not the results obtained in the case studies can be generalised in the industry.

The research results indicated that none of the case studies could fully meet the requirements in the COP. Reasons why the case study growers failed to meet the requirements in the COP include the fact that urban area growers do not have suitable release sites near their greenhouses-also, they have insufficient drained nutrient solution storage capacity in their hydroponic systems. However, whether a greenhouse with insufficient storage capacity but easy access to a suitable nutrient solution disposal site (e.g., pasture or outdoor crops) can meet the requirements in the COP remains unclear. Further case studies should be conducted in the future. Technical areas in nutrient solution management, such as irrigation water quality, disease control, and nutrient imbalance control, should be investigated in more depth in future.

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Appendices

Appendix 1 Interview Questions

1st Interview questions:

1. Could you please tell me how you came to run this property?
2. What did you do before that? (*Back to High School*)
3. What crops have you managed?
4. What area have you got in production?
5. Can you please explain how this is broken down?
6. What crops have you got in these?
7. How much area have you in tomatoes?
8. Are they all one variety?
9. Over each of your tomato crops what sort of yield are you getting?
10. What crop density (ies) do you use? How can you decide the crops' density?
11. Do you use the same irrigation system as this for all your tomatoes?
12. How does this system work?
13. What sort of media is this?
14. Do you change growing media between crops?
15. Where does your irrigation water come from?
16. Have you got a water analysis?
17. Do you have to treat the irrigation water before using it? How do you do that?
18. What kind of fertilisers are you using?
19. Do you use premixed fertiliser or do you do it all yourself
20. When you are formulating the nutrient solution, what factors are considered important?
21. Can you tell me the maximum daily use of water in summer? (Average? Winter?)
22. Is there any nutrient solution drainage occurred while irrigating?
23. Do you collect the drainage? If yes, how?
24. Do you reuse the drainage nutrient solution?

25. After collecting the drainage nutrient solution, will it be in storage for some period of time or directly reused again?
26. If you are reusing the drained nutrient solution, do you need to treat it before it is reused? If yes, how is it treated?
27. What equipment have you got here to manage the irrigation and nutrient supply system?
28. Is there anything else you need to manage the recirculation of nutrient solution?
29. Do you ever have to release surplus solution?
30. What sorts of situations does that happen in? And how often does that happen?
31. If you do dump it where does it go?

2nd Interview questions

1. What is the tomato cropping schedule in these greenhouses? How long is the harvest period?
2. What are the characteristics of irrigation management in the different tomato crop growth stages?
3. May I have a sample recipe of the Nutrient solution A, B in different crop growing stages?
4. What is the pH acceptable range in the supply nutrient solution when growing tomatoes? How do you adjust the nutrient solution pH?
5. What is the EC acceptable range in the supply nutrient solution when growing tomatoes? How do you adjust the nutrient EC?
6. How do you set up the irrigation schedule? What factors should be considered?
7. How often do you adjust the irrigation schedule in the greenhouse? What conditions does this depend upon?
8. What are the differences between summer and winter in terms of irrigation volume supplied to the tomato crops? Why are they different?
9. If you reuse the nutrient solution drainage, what percentage of the reused solution is in the supplied solution?
10. Do you have a daily nutrient solution release out of the system in this greenhouse?

11. What percentage of the nutrient solution drainage do you consider acceptable? Why? How do you control the nutrient solution drainage?
12. How often do you totally replace the nutrient solution in the system? In what situations will you do this?
13. When you release the nutrient solution, from which tank do you release it? Do you have a water meter on your release tanks? How much volume per release?
14. Do you store the waste nutrient solution before releasing it? If yes, how long do you store the release nutrient solution and why?
15. Do you analyse the composition of the dumped nutrient solution? If yes, what's the aim of the analysis?
16. Could you please offer me an overall budget of the whole irrigation system investment?
17. Do you calculate the nutrient solution release cost? If yes, how do you calculate it?

Appendix 2: Nutrient Solution Discharge in Case Study One

The total amount of water and nutrient solution in the hydroponic system includes the volume of the raw water, the volume of the mixed solution in the mixing tank, the volume of fresh nutrient solution A and B in the fresh nutrient solution tanks, the volume of nutrient solution running in pipes and in growing slabs, the volume of collected nutrient solution in the central nutrient solution storage tank, and the volume of sterilised nutrient solution in the reused nutrient solution storage tanks (Table A.1). However, when releasing nutrient solution, the volume of the discharge is not equal to the total volume of the water and nutrient solution in the whole irrigation system. Only the solution that potentially has root disease causing pathogens will be released out of the system.

Table A.1 Estimate of the nutrient solution discharge volume in Case Study One

	Capacity of the tank (m ³)	Cleanness (yes/no)	Calculated in dumping volume (yes/no)
Raw water tank	400	Yes	No
Mixing tank	1×4	Yes	No
Nutrient solution tank A	2×4	Yes	No
Nutrient solution tank B	2×4	Yes	No
Nutrient solution in pipes and slabs	500 (Estimate volume)	No	Yes
Central storage tank	200 (Keep 1/3 free)	No	Yes
Reused nutrient solution storage tank	80	Yes	No

The total amount of discharge volume includes the volume of nutrient solution running in the greenhouse pipes, nutrient solution in the growing slabs, and the volume of collected drainage in the central nutrient solution storage tank. Because the raw water is clean, its storage volume is not calculated into the releasing volume. Fresh nutrient solutions A and B are made up of pure fertiliser and clean raw water. Consequently, they are clean so neither of their volumes is calculated into the discharge volume. The sterilised nutrient solution stored in the reused nutrient solution storage tanks has been treated. Hence, its volume would not be calculated into the releasing volume either.

The capacity of the central nutrient storage tank is approximately 200 m³. It is generally kept 1/3 free so the maximum amount of nutrient solution volume in it is approximately 133 m³. There is no record of the amount of nutrient solution running in the greenhouses' pipes and slabs, but the volume is estimated by Grower One at approximately 500m³ in a 4-hectare greenhouse. Therefore a rough estimated total volume of each discharge is:

$$133\text{m}^3 \times 2/3 + 500\text{m}^3 = 633\text{m}^3 = 633,000 \text{ L}$$

Assuming that the nutrient solution has to be discharged when the Nitrate-N concentration reaches 300 mg/L, then the total Nitrate-N applied to the environment in one discharge can be estimated as:

$$633,000 \text{ L} \times 300 \text{ mg/L} = 189,900,000 \text{ mg} = 189.9 \text{ kg}$$

Assuming the maximum nitrogen application rate is 30 kg/ha every three weeks, then the required release site area is:

$$189.9 \text{ kg} \div 30 \text{ kg/ha} = 63.3 \text{ ha}$$

Assuming that the nutrient solution release frequency is once per three years in Case Study One, when the released nutrient solution needs to be stored in the system for a 4-months period in winter and a 2-weeks periods in summer, also that the storage system has a 10% capacity buffer, then the required storage capacity is:

$$633\text{m}^3 + 633\text{m}^3 \times 10\% = 696.3 \text{ m}^3$$

Appendix 3: A sample laboratory analysis result of nutrient solution drainage in Case Study One

Hill Laboratories



ANALYSIS RESULTS

Client:
 Address:
 Client Phone:

Laboratory No.
 Registered:
 Reported:
 Order No.:
 Submitted By:
 Client Ref:

Analysis	Level Found	Medium Range	Low	Medium	High
pH	5.9	5.8 - 6.6			
Electrical Conductivity (CF)	60	15 - 45			
Nitrate-N (mg/L)	432	100 - 300			
Phosphorus (mg/L)	68	25 - 75			
Potassium (mg/L)	702	150 - 450			
Sulphur (mg/L)	530	40 - 120			
Calcium (mg/L)	620	100 - 350			
Magnesium (mg/L)	218	25 - 75			
Sodium (mg/L)	54	10 - 60			
Chloride (mg/L)	59	5 - 80			
Iron (mg/L)	1.6	2.0 - 10.0			
Manganese (mg/L)	0.32	0.40 - 5.00			
Zinc (mg/L)	0.69	0.10 - 3.00			
Copper (mg/L)	0.07	0.10 - 1.00			
Boron (mg/L)	1.10	0.20 - 1.50			
Sum of Cations (me/L)	69				
Sum of Anions (me/L)	68				

The above nutrient graph compares the levels found with reference interpretation levels. NOTE: It is important that the correct sample type be assigned, and that the recommended sampling procedure has been followed. R J Hill Laboratories Limited does not accept any responsibility for the resulting use of this information.

No Laboratory Comments

Appendix 4 Nutrient Solution Discharge in Case Study Two

The nutrient solution discharge volume in Case Study Two is approximately 6 m³ per discharge. The discharge frequency is 2-3 weeks in summer and 4 weeks in winter. The tomato crop cycle is 7 months from January to July. Assuming that in summer (January to April) Case Study Two releases nutrient solution 6 times (once every 3 weeks at a volume of 6 m³ per release) and in winter (from May to July) releases 3 times (once every 4 weeks at a volume 6m³ per release), then the total discharge volume for one crop cycle is:

$$(3+6) \times 6 \text{ m}^3 = 54 \text{ m}^3 = 64,000 \text{ L}$$

Assuming that the nitrogen concentration in the nutrient solution drainage is 300 mg/L, then the nitrogen discharge volume per discharge is:

$$300\text{mg/L} \times 6,000 \text{ L} = 1,800,000 \text{ mg} = 1.8 \text{ kg}$$

Assuming that the maximum nitrogen application rate is 30 kg/ha every 3 weeks, then in summer at a release frequency every 3 weeks per release, the required release area in 3 weeks is:

$$1.8 \text{ kg} \div 30 \text{ kg/ha} = 0.06 \text{ ha}$$

In winter, at a release frequency of every 4 weeks, then the required release area in every 3 weeks is:

$$1.8 \text{ kg} \div 30 \text{ kg/ha} = 0.06 \text{ ha}$$

The total nitrogen discharge in a crop cycle is:

$$300\text{mg/L} \times 54,000 \text{ L} = 16,200,000 \text{ mg} = 16.2 \text{ kg}$$

Assuming that the nutrient solution release frequency is once every 3 weeks in summer and once every 4 weeks in winter in Case Study Two, when the released nutrient solution needs to be stored in the system for a 4-month period in winter and a 2-week period in summer, also that the storage system has a 10% capacity buffer, then:

Winter discharge volume (from May to July, release 3 times): $3 \times 6 \text{ m}^3 = 18 \text{ m}^3$

Summer discharge volume in 3 weeks: 6 m^3

Therefore the required released nutrient solution storage capacity is:

Winter: $18 \text{ m}^3 + 18 \text{ m}^3 \times 10\% = 19.8 \text{ m}^3$

Summer: $6 \text{ m}^3 + 6 \text{ m}^3 \times 10\% = 6.6 \text{ m}^3$

Appendix 5: Nutrient Solution Discharge in Case Study Three

In Case Study Three, the total 6,500 m² growing area includes four sections, with each section 500 m², 1,500m², 1,700 m², and 2,800 m². The crop density is 2.5 plants/m². Grower Three states that the average nutrient solution supply volume is 3 L/plant in summer and 0.75 L/plant in winter. The average drainage volume is 25% of the supply volume. Therefore, the plant numbers, average daily nutrient solution supply and drainage volume in summer, average daily nutrient solution supply and drainage volume in winter are calculated in Table A3.1:

Table A. 2 Average nutrient solution supply and drainage volume for Case Study Three

	Growing area (m ²)	Plant number	Average irrigation volume in summer (L/day)	Average irrigation volume in winter (L/day)	Average drainage volume in summer (L/day)	Average drainage volume in winter (L/day)
Section 1	500.0	1,250.0	3,750.0	937.5	937.5	234.4
Section 2	1,500.0	3,750.0	11,250.0	2,812.5	2,812.5	703.1
Section 3	1,700.0	4,250.0	12,750.0	3,187.5	3,187.5	796.9
Section 4	2,800.0	7,000.0	21,000.0	5,250.0	5,250.0	1,312.5
Total	6,500.0	16,250.0	48,750.0	12,187.5	12,187.5	3,046.9

There are two crop cycles in each greenhouse in Case Study Three. Grower Three states that the nutrient solution drainage occurs only in a two-month period during each crop cycle. Assuming that each greenhouse has one summer crop and one winter crop, the average drainage volume in summer is 12.2 m³ (12,187.5 litres) daily (Table A3.1). In a 2-month period the drainage volume would be 732 m³. The average drainage volume in winter is 3.0 m³ (3046.9 L) daily (Table 1). In a 2-month period the drainage volume would be 180 m³. The total drainage volume in a year is 912 m³.

Assuming that the nitrogen concentration in the drainage is 300 mg/L, then the daily nitrogen discharge in winter is:

$$300 \text{ mg/L} \times 3046.9 \text{ L} = 914,070 \text{ mg} = 0.9 \text{ kg}$$

The daily nitrogen discharge volume in summer is:

$$300 \text{ mg/L} \times 12187.5 \text{ L} = 3,656,250 \text{ mg} = 3.6 \text{ kg}$$

The annual nitrogen discharge volume is:

$$0.91 \text{ kg} \times 60 + 3.66 \text{ kg} \times 60 = 274.2 \text{ kg}$$

However, there are eight greenhouses in Case Study Three, and the cropping schedules in each greenhouse are different. Therefore, the calculated results in the previous section are just estimated numbers. Their validity remains unclear because there are no records in this case study.

Assuming that the total discharge volume in winter is 180 m^3 , when it is stored for a 4-months period and the storage system has 10% buffer capacity, the required storage capacity is:

$$180 \text{ m}^3 + 180 \text{ m}^3 \times 10\% = 198 \text{ m}^3$$

Assuming that the daily nutrient solution discharge volume in summer is $12.2 \text{ m}^3/\text{day}$, then in 2 weeks the total volume is:

$$12.2 \text{ m}^3/\text{day} \times 14 \text{ day} = 170.8 \text{ m}^3$$

The required storage capacity in summer (10% buffer) is:

$$170.8 \text{ m}^3 + 170.8 \text{ m}^3 \times 10\% = 187.9 \text{ m}^3$$