វិទ្យាស្ថានបច្ចេកវិទ្យាកម្ពុជា
INSTITUTE OF TECHNOLOGY OF CAMBODIA

GRADUATE SCHOOL
MASTER'S DEGREE OF ENGINEERING
IN
WATER AND ENVIRONMENT

MAPPING OF PESTICIDE DISTRIBUTION IN KOH THUM DISTRICT, KANDAL, CAMBODIA

A THESIS SUBMITTED BY

FRICK Melvin

UNDER CO-SUPERVISION OF

Dr. EANG Khy Eam, Dr. MASSUEL Sylvain

SEPTEMBER 2020

MAPPING OF PESTICIDE DISTRIBUTION IN KOH THUM DISTRICT, KANDAL, CAMBODIA

A THESIS PRESENTED BY

FRICK Melvin

TO
THE INSTITUTE OF TECHNOLOGY OF CAMBODIA

IN PARTIAL FULFILMENT OF THE REQUIREMENTS
FOR THE AWARD OF
MASTER'S DEGREE OF ENGINEERING

SPECIALIZATION: *Water and Environment*

SUPERVISOR: **Dr. EANG Khy Eam**
CO-SUPERVISOR: **Dr. MASSUEL Sylvain**
CO-SUPERVISOR: **Dr. PHAT Chanvorleak**

EXAMINATION COMMITTEE

Dr. CHHUON Kong, Head of HWRE, ITC		*Chair*
Dr. TY Boreborey, Lecturer-Researcher, GCA, ITC		*Reviewer*
Dr. KET Pinnara, Head of UWE Master's Program, ITC		*Reviewer*
Dr. SUONG Malyna, Lecturer-Researcher, GCA, ITC		*Reporter*
Dr. EANG Khy Eam, Lecturer-Researcher, HWRE, ITC		*Member*

PHNOM PENH, SEPTEMBER 15, 2020

អនុញ្ញាតឱ្យការពារនិក្ខេបបទ

នាយករិវទ្យាស្ថាន ៖ _____

ថ្ងៃទី   ខែ   ឆ្នាំ ២០២០

ប្រធានបទ ៖ ការធ្វើផែនទីនៃបំណែងចែកផ្ទាំសំលាប់សត្វល្អិតនៅស្រុកកោះធំខេត្តកណ្ដាល

ស្ថាបនទទួលកម្មសិក្សា ៖ **SATREPS**

នាយកសាលាក្រោយបរិញ្ញាបត្រ ៖ បណ្ឌិត ស៊ិម ទេពមុនី _____

សហសាស្ត្រាចារ្យណែនាំ ៖ ១. បណ្ឌិត អៀង យីអៀម _____

២. បណ្ឌិត **MASSUEL Sylvain** _____

រាជធានីភ្នំពេញ ឆ្នាំ២០២០

MINISTRY OF EDUCATION,
YOUTH AND SPORT

INSTITUTE OF TECHNOLOGY OF CAMBODIA

MASTER'S THESIS
Of Mr. FRICK Melvin

Defense Date: September 15, 2020

PERMISSION TO DEFEND THE THESIS

Director of Institute: _____

Phnom Penh,   2020

Thesis's Title: Mapping of pesticide distribution in Koh Thum district, Kandal

Host Institution: SATREPS

Director of Graduate School: Dr. SIM Tepmony _____

Supervisors: 1. Dr. EANG Khy Eam _____

2. Dr. MASSUEL Sylvain _____

PHNOM PENH, CAMBODIA

ACKNOWLEDGMENTS

អត្ថបទសង្ខេប

នៅប្រទេសកម្ពុជាការពង្រីកវិស័យកសិកម្មដែលគាំទ្រដោយការវិនិយោគលើហេដ្ឋារចនាសម្ព័ន្ធធារាសាស្ត្រមិនត្រឹមតែជួយដល់ការអភិវឌ្ឍសេដ្ឋកិច្ចប៉ុណ្ណោះទេថែមទាំងការផ្លាស់ប្ដូរដំណើរការធារាសាស្ត្រនៅតំបន់ទំនាបលិចទឹកដែលជះឥទ្ធិពលយ៉ាងខ្លាំងដល់ការដឹកជញ្ជូនកខ្វក់និងការរាលដាលនៃសារធាតុគីមីដែលត្រូវបានប្រើប្រាស់ក្នុងវិស័យកសិកម្ម។

ទោះយ៉ាងណាវត្តមាននិងការប្រមូលផ្ដុំសារធាតុគីមីពុលទាំងនេះចូលទៅក្នុងបរិស្ថាននៅកម្ពុជានៅតែមិនសូវទាន់បានដឹងនៅឡើយ។   ដូច្នេះការសិក្សានេះមានគោលបំណងធ្វើការស៊ើបអង្កេតអំពីស្ថានភាពបរិស្ថានទាក់ទងនឹងថ្នាំសំលាប់សត្វល្អិតក្នុងរដូវប្រាំងបន្ទាប់ពីការប្រើប្រាស់អស់រយៈពេល   ១០   ឆ្នាំ។ ទឹកពីប្រពន្ធធារាសាស្ត្រវាលស្រែដំណាំនិងទឹកក្រោមដីត្រូវបានគេប្រមូលសំណាកហើយថ្នាំសំលាប់សត្វល្អិតត្រូវបានរកឃើញដោយការវិភាគពាក់កណ្ដាលបរិមាណដោយប្រើក្រូម៉ូស្វមខ្សែនផ្សាប់នឹងម៉ាញ៉ូទិកម៉ាស់   (GC-MS)   ។   ដំបូងថ្នាំសម្លាប់សត្វល្អិតចំនួន   ៧៧ ត្រូវបានស្រង់បញ្ជីតាមរបៈបទសម្ភាសន៍កសិករនិងអ្នកលក់ថ្នាំសម្លាប់សត្វក្នុងខេត្តកណ្ដាល។ បន្ទាប់មកក្នុងចំណោមទិន្នន័យមូលដ្ឋានMSនៃម៉ូលេគុលចំនួន   ៤៥១ ថ្នាំសម្លាប់សត្វល្អិតចំនួន   ១៦៧   ត្រូវបានរកឃើញក្នុងនោះមាន   ២១ ដែលជាផ្នែកមួយនៃថ្នាំសំលាប់សត្វល្អិតដែលបានស្រង់បញ្ជីពីការសំភាសន៍ខណៈដែលថ្នាំសំលាប់សត្វល្អិតដែលរកឃើញចំនួន១៤៦   ផ្សេងទៀតគឺមិនមាននៅក្នុងបញ្ជី។ ប្រភេទសំខាន់ៗនៃដីគីមីគឺថ្នាំសំលាប់សត្វល្អិត   (៣២%),   ថ្នាំសម្លាប់មេរោគ   (២៥%) និងថ្នាំសំលាប់ស្មៅ   (២១%)   និងក្រុមគ្រួសារគីមីសំខាន់ៗគឺ   carbamates   (១៤%), organophosphates (១៣%), triazoles (១២%), organochlorines (១១%) និង pyrethroids (១១%) ។ ភាគច្រើននៃថ្នាំសំលាប់សត្វល្អិតត្រូវបានរកឃើញថាមានគ្រោះថ្នាក់មធ្យម (៤០%) ។ លើសពីនេះទៅទៀតថ្នាំសំលាប់សត្វល្អិត   ចំនួន   ១១៩ ដែលបានរកឃើញមិនត្រូវបានអនុញ្ញាតិអោយចូលក្នុងសហគមន៍អ៊ីរ៉ុបទេខណៈចំនួន   ១០ ត្រូវបានហាមឃាត់នៅក្នុងប្រទេសកម្ពុជា។

Chloroneb ដែលមិនត្រូវបានអនុញ្ញាតិនៅក្នុងសហគមន៍អ៊ីរ៉ុបត្រូវបានគេរកឃើញនៅគ្រប់សំណាកទឹកជាមួយនឹងកំហាប់ខ្ពស់ជាពិសេសនៅក្នុងទឹកក្រោមដី(៣.៤០១០   ±   ០.៣៦៥៥

μg/L) និងក្នុងទឹកកណ្ដាលព្រែក (៣.៨៣១៤ ± ០.០៨២៦ μg/L) ។ ទន្ទឹមនឹងនេះ ទន្លេបាសាក់មានភាពកខ្ជក់តិចជាងគេ (ម៉ូលេគុលចំនួន ៥៤) ខណៈពេលដែលថ្នាំសំលាប់សត្វល្អិតបានប្រមូលផ្ដុំភាគច្រើននៅក្នុងទឹករាល់ស្រែ (៩៩ ម៉ូលេគុល) ប៉ុន្តែក៏មាននៅក្នុងទឹកនៅកណ្ដាលព្រែក (៨៦ ម៉ូលេគុល) និងទ្វារបង្ហូរទឹក (៧១ ម៉ូលេគុល) ។

ទឹកនៅកណ្ដាលព្រែកត្រូវបានបំពុលដោយថ្នាំសំលាប់សត្វល្អិតដែលមានគ្រោះថ្នាក់ជាងគេដោយគិតតាមចំនួននិងសក្ដានុពលនៃការពុល។

លើសពីនេះទៅទៀតទឹកក្រោមដីបានចែកចាយថ្នាំសម្លាប់សត្វល្អិតរួមជាមួយរាល់ទីតាំងទឹកដែលជាទឹកស្ថិតនៅកណ្ដាលព្រែក។

ថ្នាំសម្លាប់សត្វល្អិតក្នុងទឹកអាចត្រូវបានដឹកជញ្ជូនរៀងខ្សោយតាមប្រឡាយព្រែកនិងពីរាលស្រែទៅព្រែក

ដោយសក្ដានុពលព្រោះតែកម្រិតទឹកទាបនិងដោយសារតែថ្នាំសំលាប់សត្វល្អិតភាគច្រើនគួរតែបំបែកខ្លួនលឿន។

ផ្ដួយទៅវិញតាមរយៈប្រព័ន្ធធរាសាស្ត្រីព្រែកប្រជាកសិករកសិករអាចនាំយកថ្នាំសម្លាប់សត្វល្អិតដែលមិនចេះរលួតមកដំណាំវិញ។

ចុងបញ្ចប់ការគំរាមកំហែងជាក់លាក់មួយចំពោះជីវៈចម្រុះការដាំដុះនិងសុខភាពមនុស្សអាចនឹងកើតមាននៅក្នុងតំបន់កសិកម្មនៃស្រុកកោះធំ។

ការវិភាគដែលផ្ដោតការយកចិត្តទុកដាក់បន្ថែមទៀតអាចត្រូវបានអនុវត្តជាមួយនឹងទិន្នន័យមូលដ្ឋាន MS ដែលមានវិសាលភាពនិងជាមួយទិន្នន័យបន្ថែមអំពីភាពជាប់លាប់នៃថ្នាំសំលាប់សត្វល្អិតនៅក្នុងទឹកនិងការពុល។

ABSTRACT

In Cambodia, the intensification of agriculture supported by investments in hydraulic infrastructures does not only contribute to the economic development, but also to a change in hydraulic processes in the floodplains, which are potentially affecting the pollutant transport and dissemination of chemicals used in agricultural sector. However, the presence and accumulation of these chemical pollutants into the environment in Cambodia remains poorly known. Therefore, this study aimed to make an investigation of the environmental state with regards to pesticides, during the dry season, after 10 years of use. Water from irrigation canal, crop field and groundwater were sampled and pesticides were detected by semi-quantitative analysis using gas chromatography coupled to mass-spectrometry (GC-MS). Firstly, 77 pesticides were inventoried through interviews of farmers and resellers in Kandal. Then, among the MS database of 451 molecules, 167 pesticides were detected including 21 which were part of the inventoried pesticides from interviews while other 146 detected pesticides were off-list. The major types of biocides were insecticides (32%), fungicides (25%) and herbicides (21%) and the major chemical families were carbamates (14%), organophosphates (13%), triazoles (12%), organochlorines (11%), and pyrethroids (11%). Most of pesticides detected were moderately hazardous (40%). Moreover, 119 pesticides detected were not allowed in European Union while 10 were banned in Cambodia. Chloroneb which was not authorized in European Union, was detected in every water sample, with particularly high concentrations in groundwater ($3.4010 \pm 0.3644\,\mu g/L$) and in water in the middle of prek ($3.8314 \pm 0.0826\,\mu g/L$). The Bassac river was the least contaminated (54 molecules), while pesticides accumulated mostly in the rice field water (99 molecules) but also in the waters in the middle of the prek (86 molecules) and the drainage gate (71 molecules). The water in the middle of the prek was contaminated by the most hazardous pesticides in terms of number and potency of toxicity. Furthermore, groundwater shared common pesticides with every water location, the most being the water in the middle of prek. Pesticides in water may be transported weakly along the prek canal and also from the rice field to the prek, potentially because of the low level of water and because most of pesticide should degrade relatively fast. Conversely, through irrigation from the prek, farmers may bring persistent pesticides back to the crops. Finally, a certain threat to biodiversity, crop renewal and human health may be present in the agricultural area of the Koh Thum district. Further focused analysis could be performed with an extended MS database and with additional data about persistence of pesticides in water and toxicity.

ABBREVIATION AND SYMBOLS

ASE	Accelerated solvent extraction
C18	Octadecyl
DAL	Department of agriculture legislation
DDTs	Dichlorodiphenyltrichloroethanes
DPPSPS	Department of plant protection sanitary and phytosanitary
DT50	Degradation Time for 50% of compound
EU	European Union
GC-MS	Gas-chromatography coupled to mass-spectrometry
GUS	Groundwater Ubiquity Score
HCB	Hexachlorobenzene
HCH	Hexachlorohexane
MAFF	Ministry of Agriculture, Forestry and Fisheries
$MgSO_4$	Magnesium sulfate
Na_2SO_3	Sodium sulfite
Na_2SO_4	Sodium sulfate
NAL	National Agriculture Laboratory of the General Directorate of Agriculture
OCPs	Organochlorine pesticides
OPPs	Organophosphorus pesticides
PCBs	Polychlorinated Biphenyls
PLS3-AC	Styrene divinyl benzene and N-vinyl acetamide with Activated Carbon
SATREPS	Science & Technology Research Partnership for Sustainable Development
SPE	Solid-phase extraction
WHO	World Health Organization

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1. Background

Pesticides are natural or chemical, organic or inorganic, substances or mixtures intended to prevent, destroy, control or repel pests, and whose functional class commonly refers to their active ingredient and the type of pest they intend to control. Pesticide residues differ from pesticide since the residues result from the degradation of the active ingredient of the pesticide (Alavanja, 2009). Pesticides were reported to be a quick, easy and relatively inexpensive solution to pest control as they have presented benefits such as improving productivity and food quality, protecting crop losses or controlling vector-borne diseases (Aktar *et al*., 2009). However, in addition to pose problems to human health through acute and chronic toxicities, pesticides as biocides have also posed problems to environment and ecosystems, through the extermination of populations of biotas even at very low doses (Carvalho, 2017; Zhang, 2018). Indeed, such molecules were responsible for acute problems, and also chronic diseases such as immune suppression, hormone disruption, diminished intelligence, reproductive abnormalities and cancer. Pesticides have been able to contaminate every part of the environment including water and soil, affecting directly or indirectly every form of life (Aktar *et al.*, 2009; Arisekar *et al.*, 2019).

Dependence on pesticides worldwide has become a problem of interest since many farmers have been trapped in the technology system established by the dominant agricultural system. (Wilson and Tisdell, 2001). The use of pesticides in the world did not stopped increasing overall since 1990, particularly in Asia where the application of pesticides were the most intense (see **Figure 1.1**). However, the quantities of pesticides applied within Asia were heterogeneous between regions, with Cambodia which had a relatively recent history in the use of such agricultural products compared to its neighboring countries (see **Figure 1.2**) (Food and Agriculture Organization of the United Nations (FAO), 2018).
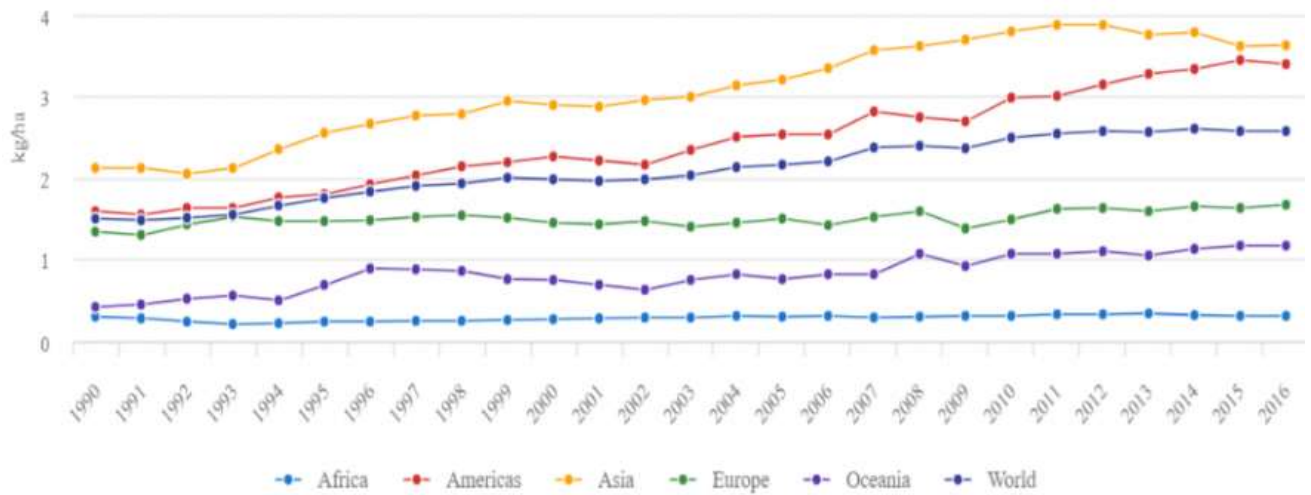
Figure 1.1. *Pesticide use per area of cropland (kg/ha), average 1990-2016* (Food and Agriculture Organization of the United Nations (FAO), 2018)
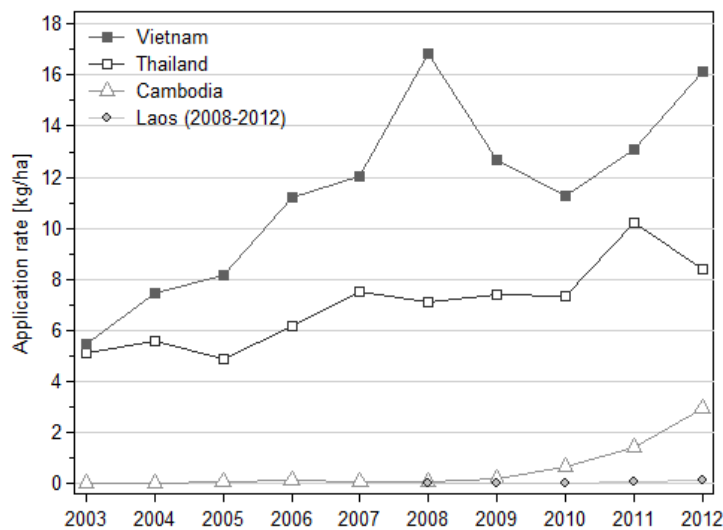
Figure 1.2. *Agricultural pesticide use in Cambodia, Laos, Thailand and Vietnam, 2003-2012* (Schreinemachers *et al.*, 2015)

The use of pesticides in Cambodia started in the early 60s. While only 7% of Cambodian famers used pesticides before 1980, they reached 49% between 1985 and 1994. Between 2002 and 2012, the import of pesticides increased by seventeen times, while most of pesticides in Cambodia were imported (legally or illegally) from countries such as Vietnam, Thailand and China, since no factories were reported in Cambodia (Preap and Sareth, 2015). Furthermore, many Cambodian farmers have experienced health problem by pesticide poisoning. Those chemicals have been extensively mis-used in term of time, strength and way

of use, because of insufficient understanding due to the lack of relevant instruction manual written in the native Khmer language (Matsukawa *et al.*, 2016). Indeed, Cambodia have faced three issues related to pesticides, which were the rapid spreading of pesticide trade associated with a weak regulatory, the strong appreciation of pesticides associated with insufficient awareness of the risks and a lack of knowledge in the use of pesticides, and the non-regular monitoring of pesticide risks (Schreinemachers *et al.*, 2015).

1.2. Objective, scope and limitation

Trough prompt economic development, Cambodia has experienced a recent and rapid spread of phytosanitary treatments in agriculture, and so representing a case study unique in South East Asia. Therefore, the challenge has been to think of a sustainable agriculture by drawing lessons from the experiences of neighboring countries already at an advanced stage. This study is located in Cambodia, in the upper Mekong delta, in the district of Koh Thum in the province of Kandal, where the agricultural intensification has been developing alongside the rehabilitation of preks irrigation system, which are perpendicular channels linking the flood plain to the river. Indeed, this area has been facing hydrological changes through a typical increase in the mobilization of water resources for irrigation, associated with a more intensive use of phytosanitary treatments. This conjunction could threaten the quality of the environment and human health in the short and medium term, and that is why this study has proposed to make an investigation of the environmental state with regard to pesticides after 10 years of use, in order to be able to make predictions and recommendations. So far, no significant data about pesticides in the prek irrigation systems of Koh Thum district were reported. The objective was then to examine pesticide molecules in different environmental compartments, in order to understand their fate in the preks irrigation system. More specifically, this study aimed to make a semi-quantitative analysis of pesticide residues in water samples collected in the river, the canals, the flooded plain, the irrigation excess return flow and the groundwater in Koh Thum district. The procedure involved filtration, followed by clean-up using SPE method, then analysis using GC-MS / MS database. Moreover, a list of available phytosanitary products was established from the local retailers and compared to the inventory for validation. However, the MS database was limited and did not include all the pesticide molecules for detection identified in the Kandal, while several data related to typical persistence of pesticides in water and groundwater leaching were not available from the scientific literature.

2. LITTERATURE REVIEW

2.1. Pesticide classification

2.1.1. Functional role

Groups of pesticides were classified according to the target pest they intend to control such as insecticides, herbicides, fungicides, rodenticides and many others (see **Table 2.1**) (Uqab *et al.*, 2016). Herbicides could affect weeds through different modes of actions such as disruption of photosynthesis or hormones responsible for growth, and also inhibition of cell division, lipids, cellulose or amino acids. Insecticides could have neurotoxic actions interfering with growth and respiration of insects. Fungicides could inhibit cell division and respiration, in addition to disrupt amino acid synthesis or carbohydrate metabolism of fungi. Rodenticides acting against rodents, could belong either to the anticoagulant family which kills of internal bleeding, or to the convulsant family which causes muscle spasms inducing coma then death (Rifai, 2013).

Table 2.1. *Classification of pesticides according to the target organism intended to control*

Type of Pesticides	Target pests
Herbicides	Weeds
Insecticides	Insects
Fungicides	Fungi
Rodenticides	Rodents
Algicides	Algae
Avicides	Birds
Miticides	Mites
Molluscicide	Snails, Slugs
Nematicide	Nematodes
Piscicides	Fish
Virucides	Virus

2.1.2. Hazard toxicity

Pesticides could also be classified according to their acute toxicity hazard category, following WHO classes: Ia (extremely hazardous), Ib (highly hazardous), II (moderately hazardous), III (slightly hazardous), U (unlikely to present acute hazard) and O (obsolete substance) (see **Table 2.2**) (World Health Organization (WHO), 2010).

Table 2.2. *Acute toxicity hazard category* (World Health Organization (WHO), 2010)

WHO Class	Meaning	LD50 for the rat (mg/kg body weight)	
		Oral	Dermal
Ia	Extremely hazardous	< 5	< 50
Ib	Highly hazardous	5-50	50-200
II	Moderately hazardous	50-2000	200-2000
III	Slightly hazardous	> 2000	> 2000
U	Unlikely to present acute hazard	≥ 5000	≥ 5000
O	Obsolete substance	/	/

2.1.3. Chemical composition

Pesticides are more generally classified according to their chemical composition, nature and major active ingredient. The classification could include OCPs, OPPs, carbamates, triazines, substituted ureas, pyrethrin and pyrethroids (Kaur *et al.*, 2019; Rifai, 2013).
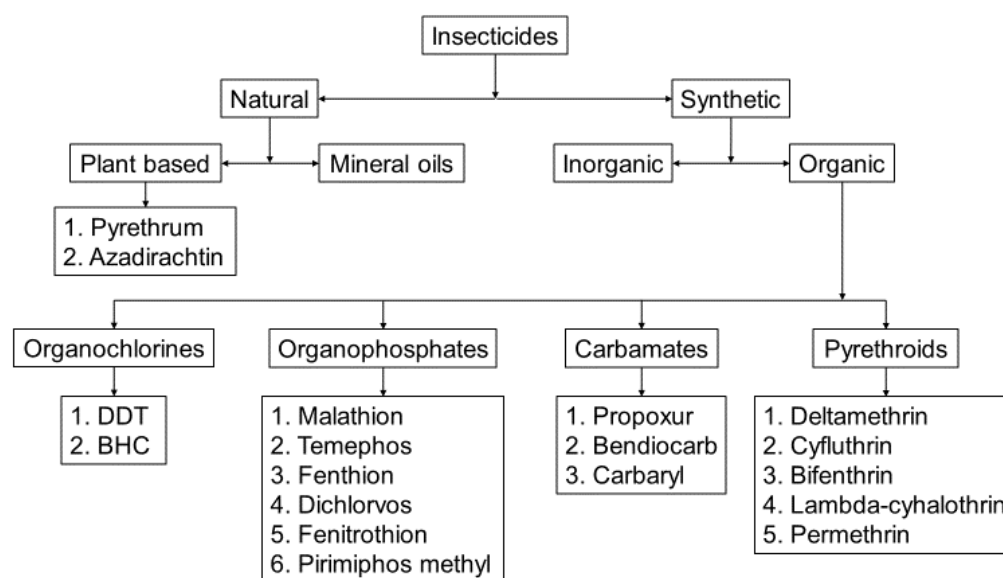
Figure 2.1. *Classification of insecticides* (Kaur *et al.*, 2019)

2.2. Organochlorine, organophosphorus and carbamates pesticides

Among the various pesticide families, OCPs were particularly noticed for their versatility, efficiency, relatively cheap price, but also for their severe toxicity, bio-

accumulation and slow degradation. They were commonly and highly used worldwide and in Cambodia as insecticide, herbicide and fungicide. OCPs were reported to be stable chlorinated hydrocarbon derivatives with low polarity, low aqueous solubility and so high lipid solubility (Jayaraj *et al.*, 2016). On another hand, OPPs which are much less persistent probably because of their unstable chemical structure, were greatly appreciated as an alternative to OCPs due to their high persistence (Carvalho, 2017). OPPs were commonly known for their high acute toxicity through the inhibition of acetylcholinesterases which are essential enzymes for seven nerve functions in many living organisms. OPPs were reported to be esters, amide or thiol derivatives of phosphoric, phosphonic, phosphorothioic and phosphonothionic acid (Adeshina *et al.*, 2019; Jayaraj *et al.*, 2016; Kwong, 2002). Carbamates, another chemical family of pesticides being even more easily degradable than OPPs, were described as aliphatic or cyclic derivatives of carbamic acid and were reported as acting similarly to OPPs through the inhibition of acetylcholinesterases, even if some carbamates were more or less toxic depending on the different types of affected living organisms (Hoffman *et al.*, 2002).

2.3. Environmental fate of pesticides

Pesticides have been able to contaminate different part of the environment such as the air, the soil, the surface water, the ground water and the sediments, harming living organisms including human, which are dependent on the affected environment. Through various ways such as emission, drift, deposition, leaching, drainage or volatilization, those molecules were able to move from one location to another (see **Figure 2.2**) (World Health Organization (WHO), 2008). Furthermore, pesticides have been able to undergo biodegradation or physico-chemical degradation to eventually produce pesticide residues. Biodegradation involves breakdown by microorganisms where as physico-chemical degradation consists in breakdown by processes in which living organisms are not involved, such as hydrolysis, oxidation-reduction, substitution, elimination, dehalogenation, and reduction without microbial intervention (Rathore and Nollet, 2012). The natural aqueous photolysis could be mentioned as example, and involves the degradation of the molecule from the absorption of photon (i.e. light energy from the sun) in aqueous medium (Rifai, 2013). Some pesticides were reported to be very persistent in the environment (particularly in soil), such as OCPs: DDT, HCH, aldrin, endrin, chlordane, DDT, heptachlor, mirex. However, environment is complex, variable and continually affected by temperature changes, weathering, living organisms, water percolation and substances added from the atmosphere; therefore, it is difficult to predict the environmental

fate of pesticides. Although the use of such contaminants would have been stopped several years ago, it would still be possible to find residues in the environment (Kutz *et al.*, 1991; Zhang, 2018). Moreover, pesticide residues have been able to bio-magnify in the aquatic organisms, affecting human health through food chain and consumption (Arisekar *et al.*, 2019). In fact, the persistence of the pesticides in the different part of the environment could depend on the physical and chemical properties, degradation and deposition rates, the environment and the climate characteristics (Kutz *et al.*, 1991; Zhang, 2018).
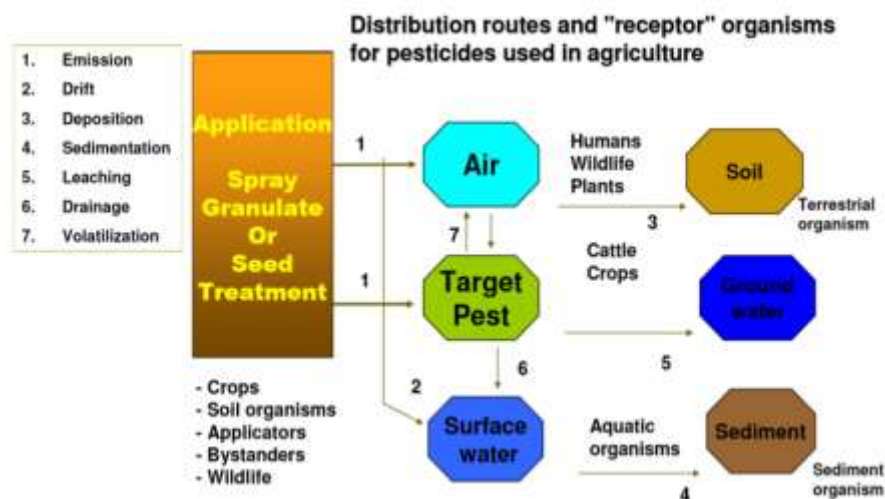
Figure 2.2. *Environmental fate of pesticides* (World Health Organization (WHO), 2008)

2.4. The Mekong river and the Bassac river

The Mekong River, about 4900 km long and crossing Cambodia from North to South, originates on the Tibetan plateaus to end up in the South China Sea, passing through China, Myanmar, Laos, Thailand, Cambodia and Vietnam by draining around 795,000 km^2 of water per year. Moreover, the Bassac river splits from the Mekong river mainstream, at the top of the Mekong delta, whose position were defined near Phnom Penh, capital of Cambodia. The Bassac river originates at the meeting point between the Mekong river and the Tonle Sap river, which is located in the province of Kandal, which includes 11 districts, each divided into communes and villages (see **Figure 2.3**) (Mekong River Commission, 2010).
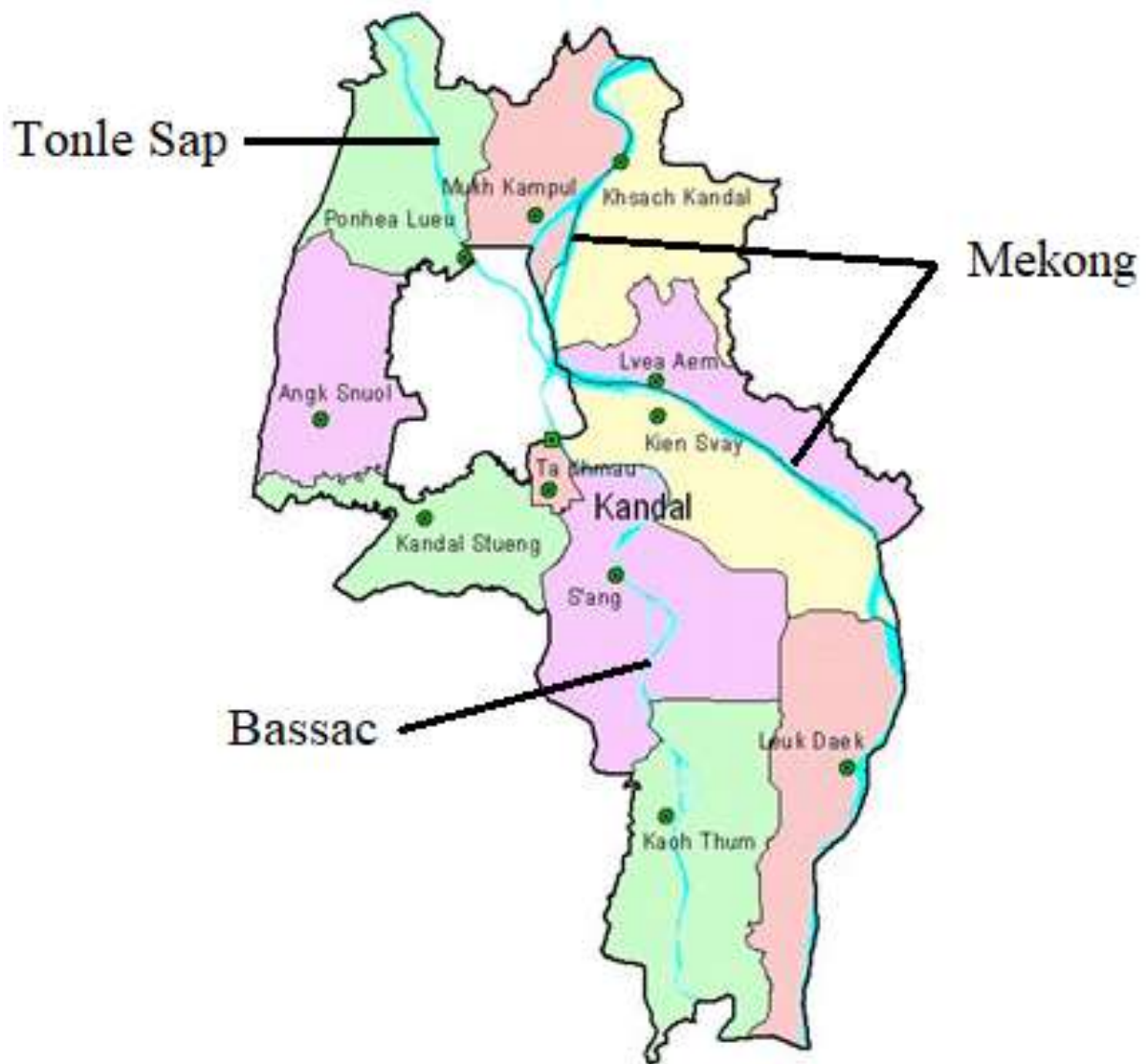
Figure 2.3. *Kandal Province and its rivers*

2.5. The prek irrigation systems

The prek systems have been canals built perpendicular to the Bassac river during the French colonial period, originally to extend the cultivable areas, then today making it possible to irrigate the crops located on the high banks of the alluvial plain called " chamcar" as well as the low plain called "boeung" (see **Figures 2.4** and **2.5**). Various rehabilitation programs were funded to make water available in the preks longer and to the increase crop production, in order to reduce poverty through agricultural development (Pratx, 2017).
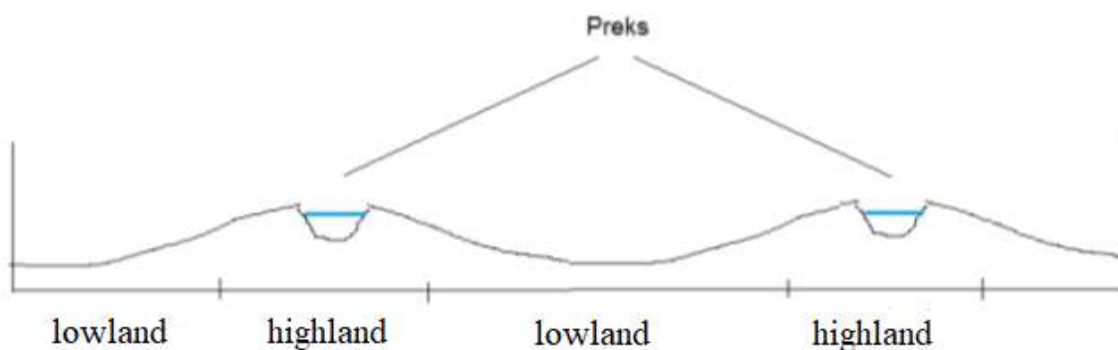
Figure 2.4. *Cross section between two preks* (Pratx, 2017)
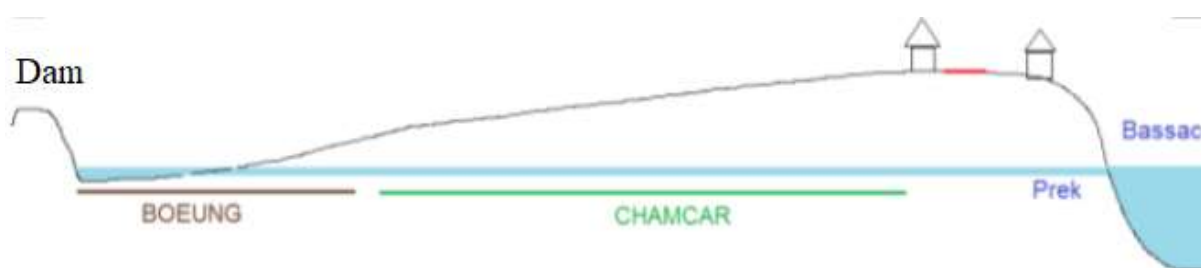
Figure 2.5. *Longitudinal section of a prek* (Pratx, 2017)

2.6. Institutional framework and regulation of pesticides in Cambodia

Ministry of Agriculture, Forestry and Fisheries (MAFF) manages pesticide regulation in Cambodia, which is divided into three departments: the Department of Agriculture Legislation (DAL) which is in charge of pesticide registration, the Department of Plant Protection Sanitary and Phytosanitary (DPPSPS) which acts as technical advisor in pest management, and the National Agriculture Laboratory (NAL) of the General Directorate of Agriculture which is responsible for pesticide analysis (Preap and Sareth, 2015). Since the Stockholm Convention in 2004, most organochlorine pesticides were banished in the world, excepted the p-p'DDT for disease vector control and the heptachlor as biocide in buildings, dams and roads or as additives in plywood adhesives (Tran *et al.*, 2019). On August 25th, 2006, Cambodia approved the Stockholm Convention and so, in 2009 no pesticides, namely aldrin, dieldrin, endrin, heptachlor and HCB should have been neither produced nor used (Idowu *et al.*, 2013). In addition, since 2012, the pesticides namely HCH, DDTs, isoxathion, and methyl-parathion were banned in Cambodia as seen in **Table 2.3** (Preap and Sareth, 2015).

Table 2.3. *List of pesticides banned in Cambodia since 2012* (Preap and Sareth, 2015)

Name of pesticides banned/deregistered in Cambodia from 2012			
Azinphos methyl	Chlordane	Demeton-s	Fensulfothion
Aldicarb	Chlordecone	Demeton-s-methyl	Fentin hydroxyde
Aldoxycarb	Chlordimeform	Diamidafos	Fluoroacetamide
Aldrin	Chlorethoxyfos	Dichlorophene	Fonofos
Aminocarb	Chlorefenvinphos	Dieldrin	Fosthietan
Amitraz	Chlorophenols	Difenacoum	Furathiocarb
Amitrol	Chlormephos	Difenthialone	beta-HCH
Antu	Chlorbenzilate	Dimefox	HCH
Aramite	Chlorophacinone	Dimethilan	Heptachlor
Arsenic compound	Chlorthiophos	Dinoxeb	Hexachlorobenzene
Benomyl	Copper arsenate	Dinoterb	Isobenzan
Binapacryl	Coumaphos	Dioxathion	Isodrin
Bromethalin	Crimidine	Edifenphose	Isoxathion
Bromophos	Crotoxyphos	Elemental phosphorous	Leptophos
Butoxycarboxim	Cupric acetoarsenite	Endosulfan	Lindane
Cadmium compound	Cyanthoate	Endothion	Medinoterb acetate
Cadusafos	Cycloheximide	Endrin / Nendrin	Mephospholan
Calcium arsenate	Cyhexatin	EPN	Mercaptofostion
Calcium cyanide	Daminozide	Ethoprop (Ethoprophos)	Methiocarb
Camphechlor	Dibromochloropane	Ethylene dichloride	Methomyl
Captafol	DDT	Ethylene oxide	Mevinphos
Captan	Demephion-o	Famphur (Famophos)	Mexacarbate
Carbon tetrachloride	Demephion-s	Fenamiphos	Methamidophos
Carbophenothion	Demeton-o	Fenbutatin oxide	Monocrotophos

2.7. Water quality standards for pesticides

Drinking water standards concerning pesticides has varied from one regulation to another. The European regulation limits each individual pesticide (other than organochlorine compounds) to 0.10 µg/L, while the standard for total individual pesticides has been 0.50 µg/L; the standard for organochlorine compounds has been 0.030 µg/L, even though they should no longer be found in Europe (Northern Ireland Environment Agency, 2011). The WHO and US EPA regulations have limited each individual pesticide to different specific values (US EPA, 2018; World Health Organization (WHO), 2018). The Cambodian regulation from 2004 also limited some individual pesticides to specific values (Kingdom of Cambodia, 2004) (see **Appendix A)**, some of which were modified since 2012.

2.8. Procedures for pesticide analysis in water samples

2.8.1 Sample transportation, storage and preparation

In previous works, the water samples were commonly transported in ice condition (~4ºC), filtered to remove debris and organic substances, then stored at 4ºC (Darko *et al.*, 2008; Jin *et al.*, 2019; Kafilzadeh, 2015; Liu *et al.*, 2016; Ntow, 2005).

2.8.2. Extraction

Most of previous studies did not perform preliminary pesticide extraction on water samples since the Solid-phase Extraction (SPE) was effective enough to extract or purify the pesticides prior to analysis (Darko *et al.*, 2008; Jin *et al.*, 2019; Kafilzadeh, 2015; Keo, 2019; Liu *et al.*, 2016); excepted in few studies which still performed a liquid-liquid partition with organic solvent such as dichloromethane (Adeshina *et al.*, 2019; Arisekar *et al.*, 2019).

2.8.3. Clean-up method prior to pesticide analysis

2.8.3.1. Principle of SPE

The SPE allows the extraction, clean-up and concentration of analytes (pesticide residues) from a complex matrix (sample), prior to their detection through Gas-chromatography coupled to Mass-Spectrometry (GC-MS). It should also improve recovery percentages. In order to separate the analytes from the interferents, SPE uses the difference of interaction for a solid phase called sorbent between analytes and interferents or impurities (Żwir-Ferenc and Biziuk, 2006) . The cartridge is first conditioned with the solvent, to wet the sorbent; then, the sample solution containing the analytes percolates through the sorbent, to retain the impurities or interfering components; the sorbent is next washed to remove the impurities, and a last elution allows to collect the analytes solution (see **Figure 2.6**).
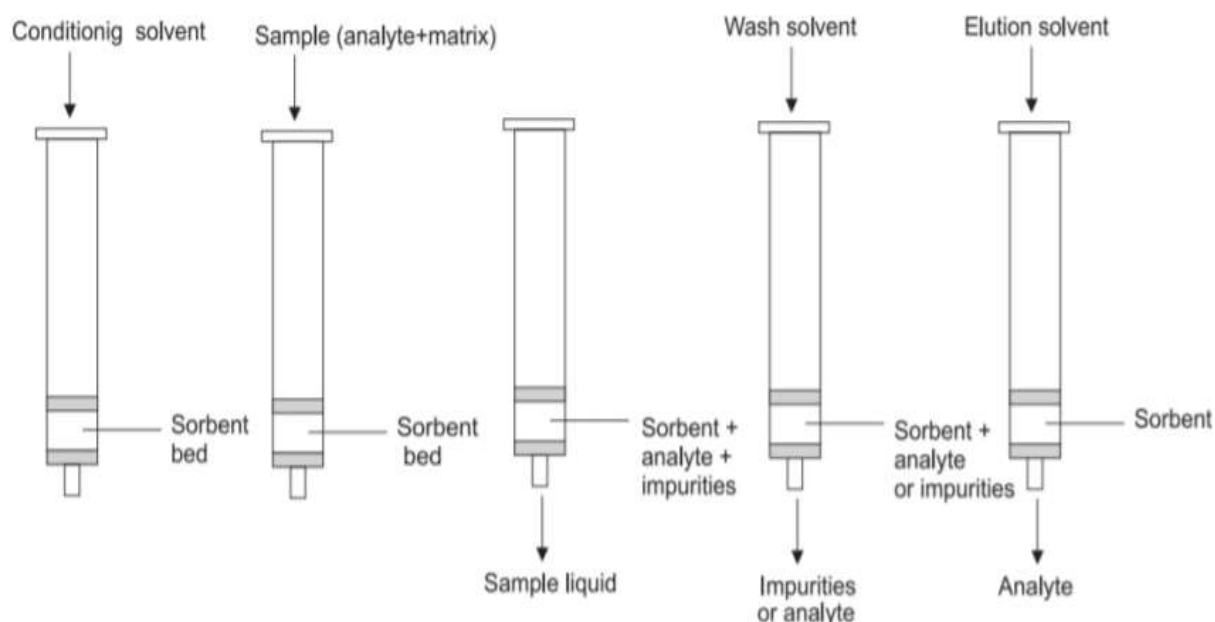
Figure 2.6. *Procedure of SPE* (Żwir-Ferenc and Biziuk, 2006)

2.8.3.2. Clean-up methods

Various types of clean-up method were used to purify pesticide compounds (OCPs, OPPs, PCBs) from water samples. The most common method has been the use of SPE with octadecyl (C18) sorbent cartridge in elution column (Arisekar *et al.*, 2019; Darko *et al.*, 2008; Kafilzadeh, 2015; Keo, 2019; Ntow, 2005). Jinya (2013) carried out the purification of 202 semi-volatile organic compounds with PLS3-AC cartridges. Another clean-up method has been used, such as the use of florisil (magnesium oxide MgO, silicon dioxide SiO_2, sodium sulfate Na_2SO_4) column chromatography (Jin *et al.*, 2019; Kangwon National University, 2011). Another method was carried out with alumina-silica gel column chromatography (Liu *et al.*, 2016). The solvent was organic, being mostly pure or mixed hexane and dichloromethane. Sodium sulfate (Na_2SO_4), sodium sulfite (Na_2SO_3) or magnesium sulfate ($MgSO_4$) were also used during the elution in order to separate the solvent layer and to improve the recovery of target compounds. Before analysis, the samples were subject to evaporation under nitrogen stream with rotary evaporator. There are also other types of extraction methods from water samples (see **Table 2.4**) (Samsidar *et al.*, 2018).

Table 2.4. *Extraction methods for pesticides from water samples* (Samsidar *et al.*, 2018)

Extraction method	Advantages	Disadvantages	Matrix
LLE Liqui-Liquid Extraction	Simple and reliable, Adaptable, Compatible with majority of instrument	Large volume of solvents, Time consuming	Water Sediment Fruits Vegetables
SPE Solid-Phase Extraction	Less time consuming than LLE, Effective purification and pre-concentration	Requires pre-treatment, Toxic organic solvents	Water Fruits Vegetables Roots
SPME Solid-Phase Microextraction	Solvent-free, Simple, Easy to use, Fast, Portable	Quite fragile of fiber, Limited lifetime	Water Fruits Vegetables Soil
DLLME Dispersive Liquid-Liquid Microextraction	Simplicity, Minimal volume of toxic solvents, High speed extraction, Inexpensive	Low efficiency of extraction	Water Fruits Vegetables Soil
SDME Single Drop Microextraction	Quick and cheap, Easy to operate, Little organic solvents, Renewability of extraction phase	Quite long extraction time	Water Soil

2.8.4. Detection of pesticides

2.8.4.1. GC-MS principle

GC-MS is an instrumental technique that includes gas chromatography coupled with mass spectroscopy, whereby relatively low molecular weight, sufficiently volatile and thermally stable compounds can be separated, identified and quantified from complex mixtures. The sample solution is injected into the GC inlet, where it is vaporized and swept onto a column by the carrier gas; then, the sample flows through the column and the compounds of interest are separated according to their relative interaction with the coating of the column called stationary phase and the carrier gas called mobile phase; the later part of the column passes through a heated transfer line and ends at the entrance of the ion source where compounds eluting from the column are converted to ions by either electron ionization or chemical ionization; next, a filter separates the positively charged ions according to various mass related properties depending on the analyzer that is used, to finally enter a detector that amplifies signal; the detector sends information to a computer that record data and converts the

electrical impulses into visual displays and hard copy displays (see **Figure 2.7**) (Hussain and Maqbool, 2014).
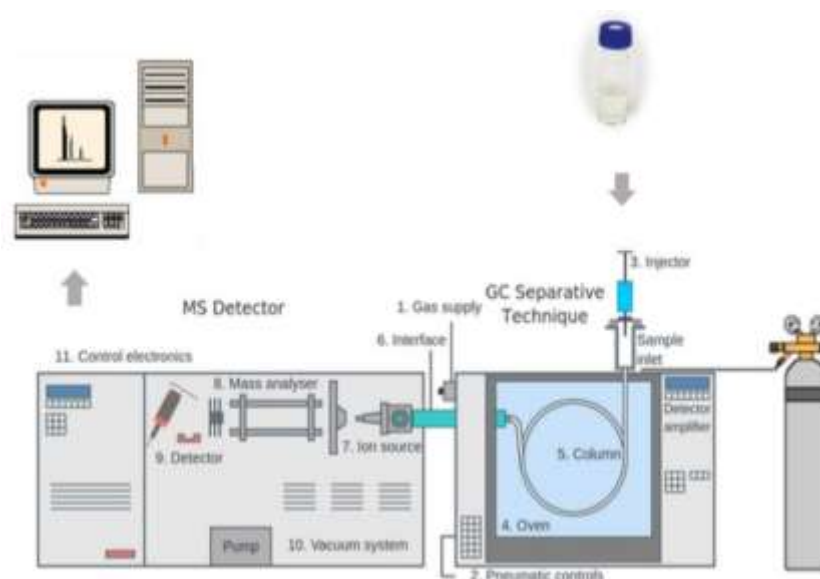
Figure 2.7. *General GC-MS diagram*

2.8.4.2. Previous detection methods used

Gas chromatography, either coupled to mass spectrometry (MS) detector or electron capture detector (ECD) have been used so far. In order to identify unknown compounds, MS (SIM mode) were proven to be effective, although ECD were little more sensitive and so more effective for quantification of some pesticides such OCPs (aldrin, dieldrin, chlordane, dicofol) and OPPs (methyl chlorpyrifos, dimethoate, methidathion and methyl parathion) (Alves *et al.*, 2012)

2.9. Data about pesticide molecules identified in Koh Thum district

77 pesticides molecules were identified for use in Koh Thum district (see **3. Methodology**) and some characteristics such as toxicity hazard, typical persistence in water phase, and ground water leaching were collected from literature, in order to understand and discuss their behavior related to human health and their environmental fate.

2.9.1. Toxicity hazard

Most of pesticides identified in Koh Thum district belonged to WHO class II (moderately hazardous), while many of them belonged to WHO class U (unlikely to present acute hazard) and some belonged to WHO class III (slightly hazardous). No pesticides were identified as belonging to WHO class Ia (extremely hazardous). Nevertheless, Abamectin and Zinc phosphide belonged to WHO class Ib which are highly hazardous (see **Table 2.5**) (University of Hertfordshire, n.d.; World Health Organization (WHO), n.d.).

Table 2.5. *Toxicity of pesticide molecules from interviews*

WHO Class	U	II	III	Ib	Ia
Biocide	Validamycin A, Mancozeb, Cyhalofop Cyhalofop-butyl, Azoxystrobin, Chlorantraniliprole, Fenclorim, Carbendazim, Penoxsulam, Methoxyfenozide, Chlorfluazuron, Pretilachlor, Niclosamide-olamine, Bensulfuron-methyl, Chlorothalonil, Spinetoram, Hexythiazox, Propineb, Kasugamycin, Pyrazosulfuron-ethyl	Chlorpyriphos, Imidacloprid, Cypermethrin, Chlorphenapyr, Acetamiprid, Cymoxanil, Difeconazole, Indoxacarb, Propiconazole, Fipronil, Isoprothiolane, Permethrin, Pyridaben, Metalaxyl, Bentazone, Propanil, Paclobutrazol, Isoprocarb, Fenobucarb, Thiacloprid, Bifenthrin, Prochloraz, Nytenpyram, 2,4-D, Imidazole, Phenthoate, Metaldehyde, Paraquat, Profenofos, Trichlorfon, Haloxyfop-R-methyl	Glyphosate, Butachlor, Hexaconazole, Buprofezin, Cyromazine, Quinclorac, Bispyribac-sodium, Metolachlor	Abamectin, Zinc phosphide	/

2.9.2. Typical persistence in water phase

NPIC, n.d.; PubChem, n.d.; University of Hertfordshire, n.d.; US EPA, 2013 provided information about typical DT50 (Degradation Time for 50% of compound) in water phase (see **Figure 2.8**) of the molecules identified in Koh Thum district, allowing to understand how long they could degrade in water. The DT50 is the time required for the chemical concentration under defined conditions to decline to 50% of the amount at application, and the term "typical" is often a mean of all studies. Those displayed data should be assimilated with caution and do not necessarily reflect the reality in this study since they are representative of characteristic examples; they can therefore change according to the complexity of the environments. However, they make it possible to have an overview of the behavior of the identified molecules, in order to predict the pesticide residues potentially expected to be found in this study. Data

about some pesticides identified in interviews remained unknown since the information were not available in scientific literature; their typical DT50 in water phase were not displayed. Thus, in water-phase only, thiacloprid, a banned molecule, was found to be particularly and very highly persistent, meaning that it would most likely be detected. Triazole, hexaconazole, lufenuron, metolachlor and fipronil were also banned pesticides, and expected to be found since they were reported to be generally highly persistent; in addition to paclobutrazol, bentazone and metalaxyl which were authorized. Moreover, permethrin, thiamethoxam and ethoxysulfuron could be found because they have a moderate persistence, although they were banned; in addition to chlorantraniliprole, imidacloprid, bispyribac-sodium, buprofezin, metalaxyl-M and bensulfuron-methyl which were authorized. Other compounds would not be found since they degraded quickly or very quickly in water, unless they were used recently.
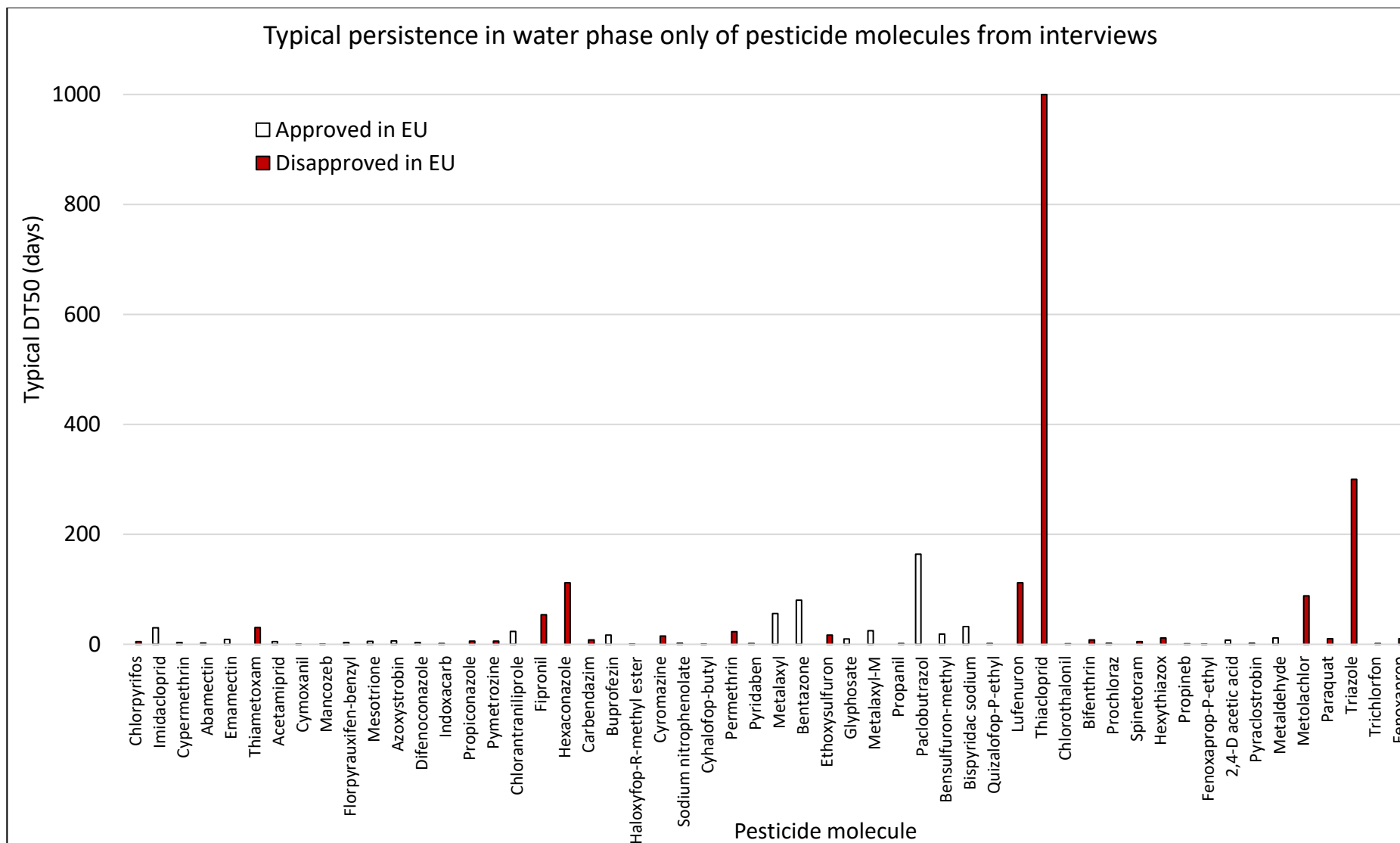
Figure 2.8. *Typical persistence in water phase only of molecules from interviews*

2.9.3. Potential groundwater leaching

NPIC, n.d.; PubChem, n.d.; University of Hertfordshire, n.d.; US EPA, 2013 provided the Groundwater Ubiquity Score (GUS), allowing to rank pesticides for their potential to move toward groundwater. When the GUS is below 0, the potential is very low; when it is between 0 and 1.8, the potential is low; when it is between 1.8 and 2.8, the potential is moderate; and when it is above 2.8, the potential is high (see **Figure 2.9**). Then, quinclorac was the compound the most expected to be found in groundwater, rather than in surface water. Thiamethoxam, azoxystrobin, chlorantraniliprole, methoxyfenozide, metalaxyl, 2,4-D acetic acid, metolachlor and trichlorfon had a high potential to leach into groundwater. Fipronil, hexaconazole, carbendazim, bentazone, ethoxysulfuron, metalaxyl-M, oxolinic acid, paclobutrazol, pyrazosulfuron-ethyl and nitenpyram could also leach into the ground water, and the other compounds would not be expected to leach into the ground water due to their low or very low potential.
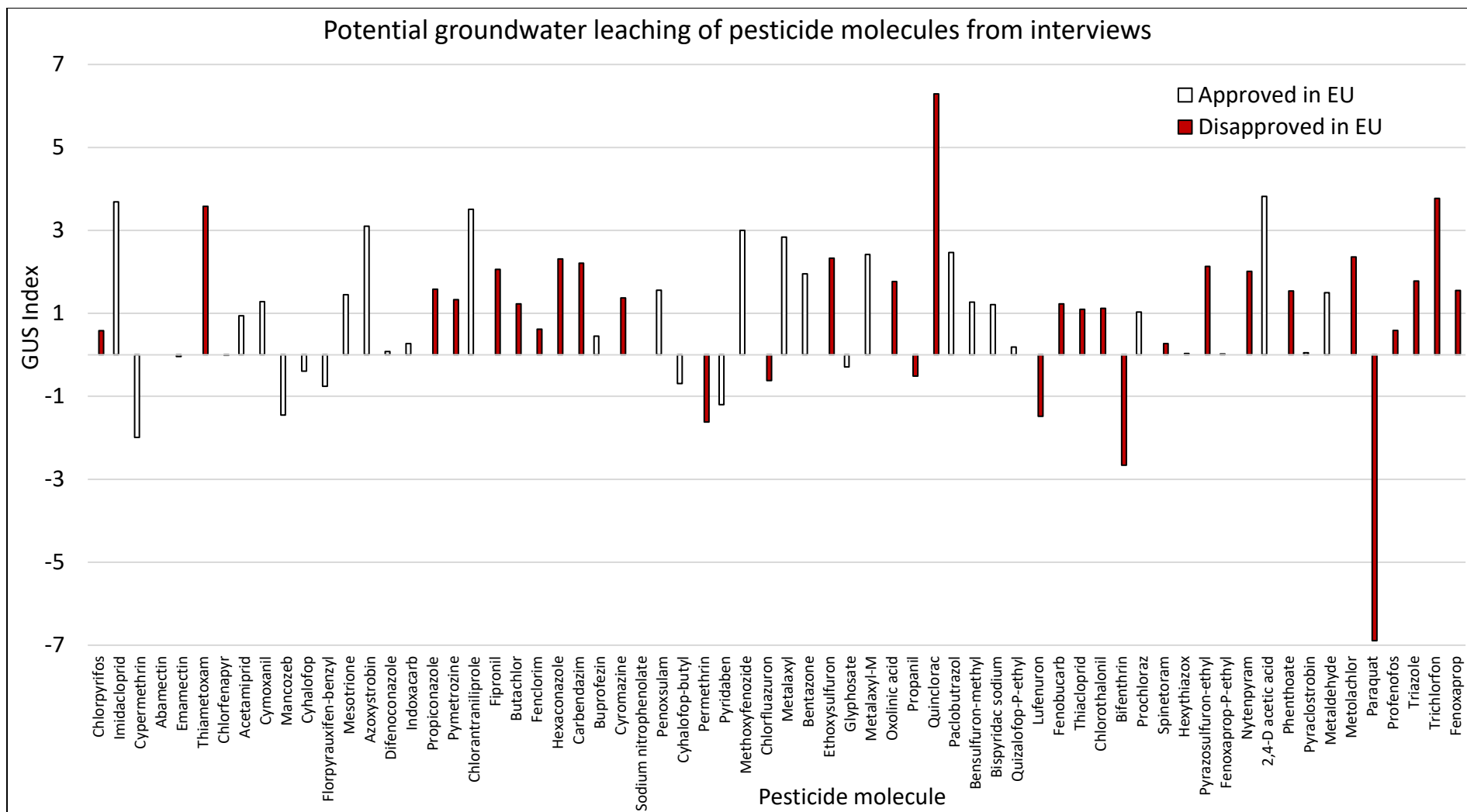
Figure 2.9. *Potential groundwater leaching of pesticide molecules from interviews*

3. METHODOLOGY

3.1. Study Area and Experimental design

The study area is located in Kandal (Cambodia), in the prek systems in the Koh Thum district. Water samples were collected at 6 different locations which were representative of rehabilitated preks (see **Figure 3.1**):

- In the Bassac river, at the east entrance of prek Chann
- At the prek Chann drainage gate
- In the middle of prek Touch
- At the western end of prek Touch
- In a rice farm field of Prek Touch (surface water)
- In a mango farm along prek Touch (groundwater)

Figure 3.1. *Prek systems in Koh Thum district, Kandal, Cambodia*

The design of the study is displayed in **Figure 3.2**. Briefly, water samples were firstly collected during the dry season, then filtrated to be preserved before extraction. The extraction allowed to remove impurities and retain the molecules of interest (pesticides) for analysis by GC-MS.
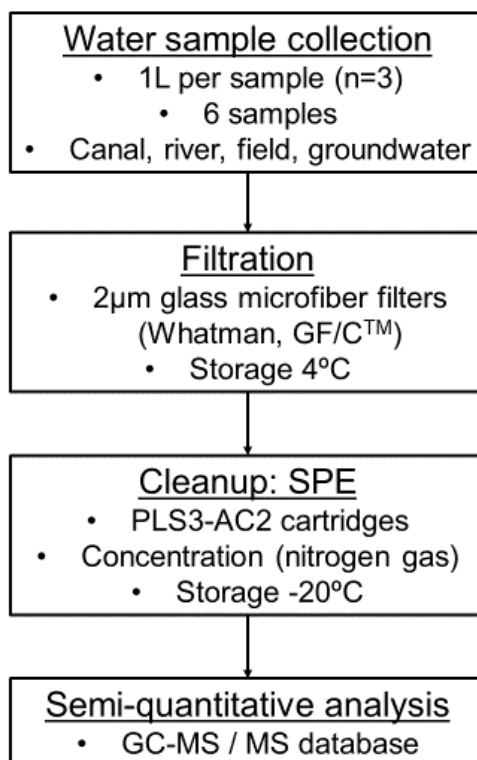
Figure 3.2. *Experimental design for the study*

3.2. Chemical list for sample preparation

Chemicals ordered and used for SPE and sample preparation prior to GC-MS analysis are shown in **Table 3.1**. Quantities were evaluated for 18 water samples with 3 replications for each and collected at 6 different locations.

Table 3.1. *List of chemicals for sample preparation*

No	Description	Pack Unit	Quantity	Brand	Quantity needed
1	**Cartridges PLS3 - 200mg/6mL**	30	1	InertSep	18 cartridges
2	**Cartridges Slim-J Active Carbon (AC) - 400mg**	50	1	InertSep	18 cartridges
3	**Dichloromethane, ACS BASIC**	4L	1	Sharlau	144mL (8mL/sample)
4	**Acetone, ACS BASIC**	4L	1	Sharlau	180mL (10mL/sample)
5	**n-Hexane, HPLC grade**	2.5L	1	Sharlau	180mL (10mL/sample)
6	**Sodium sulfate anhydrous, PA**	1Kg	1	Merck	36g (2g/sample)
7	**Nitrogen gas**	50L	2	PP air	50L (~50L/18 samples)

3.3. Sample collection

The water samples were collected on March 20th, 2020, during the dry season, by using 1L plastic bottles. They were collected in the Bassac river at the east entrance of prek Chann, at the drainage gate of prek Chann, in the middle and in the west of prek Touch, in a rice farm of prek Touch, and in the groundwater of mango farm of prek Touch. Once collected, the samples were directly filtrated through 2µm multilayered glass microfiber filters (Whatman, GF/C^{TM}) in order to remove debris and suspended material **(see Appendix B)**, transported to SATREPS laboratory in the Institute of Technology of Cambodia in iced condition, then stored at 4 ºC.

3.4. Clean-up procedure

The samples were proceeded to clean-up (purification) by solid-phase extraction (SPE) method following the method of Jinya, 2013. Sodium phosphate buffer solution (pH=7, 1mol/L) was added to the water samples and left for rest for 1h. The sorbents PLS3 and AC in their respective cartridges were activated by conditioning with 5 mL of dichloromethane, 5 mL of acetone and two times 5mL of distilled water. The samples were next passed through the cartridges at the flow rate of about 15 mL/min **(see Appendix B)**. The cartridges were dried using nitrogen gas stream for 30 min. After that, the dried cartridges were disassembled and washed: 2 mL of acetone followed by 5 mL of dichloromethane for the PLS3 cartridge **(see Appendix B)**, while both of the cartridges PLS3 and AC were washed with 5 mL of acetone. The mixed eluted solvent was collected and concentrated to approximately 1 mL, using nitrogen gas stream. Then, 10 ml of hexane were added to the previous concentrated solution of 1 ml, to be then dehydrated by elution through sodium sulfate. The solution obtained was concentrated to 1mL using nitrogen gas stream, and finally transferred into vials; stored at -20ºC.

3.5. Calibration for semi-quantitative analysis

A 1ppm mixture of standard pesticides containing about 950 molecules similar to those to be detected was added to the samples. In addition, an external calibration was performed with 1ppm, 0.5ppm, 0.125ppm, 0.1ppm, 0.05ppm and 0.025ppm solutions containing 24 target pesticides; to which was also added 10ppm mixture of standard pesticides containing the other

similar pesticides (**see Appendix B**). Thus, a quantitative analysis could be performed on the 24 target pesticides (see **Table 3.2**) while other pesticides could be detected in a semi-quantitative way.

Table 3.2. *Target pesticides for external calibration of quantitative analysis*

No	Name
1	Methamidophos
2	o,p'-DDT
3	Metalaxyl
4	Isoxathion
5	Hexachlorobenzene
6	Heptachlor
7	Aldrin
8	Dieldrin
9	Endrin
10	Chlordane
11	Chloroneb
12	Atrazine
13	Terbacil
14	Methyl-parathion
15	Parathion
16	Pyroquilon
17	Anilofos
18	Azaconazole
19	Isazofos
20	Mefenoxam
21	BHC/HCH (α, β, γ, δ)
22	Lindane
23	Malathion
24	Triadimefon

3.6. Detection procedure

The detection procedures was inspired from Jinya, 2013, and involves GC-MS device, model TQ8040 series (Shimadzu, Japan), with MS database for identification of 451 pesticide residues. The column was DB-5ms, whose length was 30m, thickness 0.25μm and diameter 0.25mm. Injection was splitless with volume 1μL. The temperature of the oven containing the column was maintained for 2 minutes at 40°C, then reached 310°C (maintained for 5 minutes) at a speed of 8°C/min. The flow rate of the carrier gas, ultra-pure helium, was 50mL/min, and the GC column flow rate was 1.23 mL/min. The MS ion source temperature was 200°C, and the MS interface temperature was 300°C. The MS event time scan measurement was 0.3sec

and the scanned mass range (m/z) was from 33 to 600. The identification of pesticide residues was performed by the data treatment system and the computer, which calculate the monoisotopic mass, predict the structural formula of compounds, and compare them using the MS database.

3.7. Pesticide molecules identified for use in Koh Thum

A non-exhaustive list of 77 molecules was established from pesticide products used by farmers and sold by retailers in the Koh Thum district (see **Table 3.3**). Those pesticides were used to treat different kind of pest including insects, herbs, fungi, bacteria, mites, mollusks and rodents. Among those 77 molecules identified, only 37 were detectable because they were included in the MS database, while 40 were undetectable The list included about 28 different organochlorine molecules contained into 63 products, 4 neonicotinoid molecules contained into 16 products, 4 pyrethroid molecules contained into 11 products, 1 organophosphorus molecule named glyphosate contained into 4 products which were largely applied in field according to the farmers and retailers, 3 organophosphate molecules contained in 11 products, 4 micro-organism derivative molecules contained into 16 products, 6 urea molecules contained into 10 products, 5 carbamate molecules contained into 5 products, 6 aryloxy phenoxy propionate molecules contained into 10 products, 1 strobilurin molecule called azoxystrobin contained into 5 products, and other molecules; some of which containing many nitrogen atoms and aromatic cycles. All the molecules identified were tolerated in Cambodia, while 32 were not approved and 7 were not registered in the European Union (European Comission, n.d.).

Table 3.3. *Pesticide molecules identified in Koh Thum district, through interviews*

Biocide	Detectable (in MS database)		Undetectable (out of MS database)	
	Approved in EU	**Disapproved in EU**	**Approved in EU**	**Disapproved in EU**
Insecticide	Cypermethrin - Buprofezin - Acetamiprid - Indoxacarb - Pyridaben	Chlorpyrifos - Chlorfenapyr - Bifenthrin - Phenthoate - Profenofos - Thiamethoxam - Fipronil - Cyromazine - Isoprocarb - Fenobucarb - Trichlorfon - Isoprothiolane	Abamectin - Imidacloprid - Emamectin benzoate - Chlorantraniliprole - Methoxyfenozide	Pymetrozine - Permethrin - Chlorfluazuron - Lufenuron - Thiacloprid - Spinetoram - Hexythiazox - Nytenpyra - Imidazole
Herbicide	Cyhalofop-butyl - Bentazone - Quizalofop-P-ethyl - Fenoxaprop-P-ethyl	Butachlor - Pretilachlor - Propanil - Metolachlor	Cyhalofop - Mesotrione – Florpyrauxifen-benzyl – Haloxyfop-R-methyl - Penoxsulam - Glyphosate – Bensulfuron-methyl - 2,4-D acetic acid - Bispyribac sodium	Fenclorim - Ethoxysulfuron - Quinclorac - Paraquat - Pyrazosulfuron-ethyl - Fenoxaprop
Acaricide	Cypermethrin - Buprofezin - Pyridaben - Hexythiazox	Chlorpyrifos - Chlorfenapyr - Bifenthrin - Phenthoate - Profenofos - Permethrin	Abamectin - Emamectin benzoate	Lufenuron
Fungicide	Azoxystrobin - Difenoconazole - Metalaxy - Metalaxyl-M - Paclobutrazol - Prochloraz - Pyraclostrobin	Propiconazole - Hexaconazole - Cyromazine - Chlorothalonil	Cymoxanil - Mancozeb	Validamycin A - Carbendazim - Bismerthiazol - Oxolinic acid - Niclosamide-olamine - Kasugamycin - Propineb - 1H-1,2,4-Triazole - Isoprothiolane
Bactericide	/	/	Emamectin benzoate	Bismerthiazol - Oxolinic acid - Kasugamycin
Molluscicide	/	/	Metaldehyde	Niclosamide-olamine - Thiacloprid
Rodenticide	/	/	Zinc phosphide	/

3.8. Statistical analysis

All essays were carried out in triplicate, and the results were expressed as mean ± standard deviation. Single-factor analysis of variance (ANOVA) were performed to test the differences between mean concentrations of pesticides, for completely randomized design (CRD) using Excel Data analysis software. A p-value < 0.05 was considered statistically significant for every sample location.

4. RESULTS AND DISCUSSION

4.1. pH of samples

The pH of water samples was overall neutral, varying between 6.86 and 7.8. The water of the drainage gate was the most basic (7.8) while the water of prek Touch west was the most acidic (6.86). The pH seemed to increase slightly from the Bassac river (7.49) towards the middle (7.76) and the drainage gate of the prek (7.8), then decreased towards the west (6.86); while surface water in the rice farm and the groundwater in the mango farm remained more neutral (7.14 and 7.12) (see **Table 4.1**).

Table 4.1. *pH of water measured at the sample locations*

Sample location	Bassac river	Middle prek (Touch)	Drainage gate (prek Chann)	West prek (Touch)	Rice farm field	Mango farm groundwater
pH	7.49	7.76	7.8	6.86	7.14	7.12

4.2. General profile of pesticides detected in Koh Thum district

In the area of Koh Thum, 167 molecules were detected, the majority of which were insecticides (32%), then fungicides (25%) and herbicides (21%). Acaricides represented 14%, nematicides were 3% and a further minority included bactericides, molluscicides and plant growth regulators (see **Figure 4.1**). Carbamates (14%), organophosphates (13%), triazoles (12%), organochlorines (11%), and pyrethroids (11%) were the most present chemical family of the pesticides detected. Moreover, pesticides moderately hazardous were detected as predominant (40%), followed by slightly hazardous (16%) and unlikely to present acute hazard (16%); highly hazardous pesticides detected represented 8% and extremely hazardous pesticides 1% (see **Figure 4.2.**).
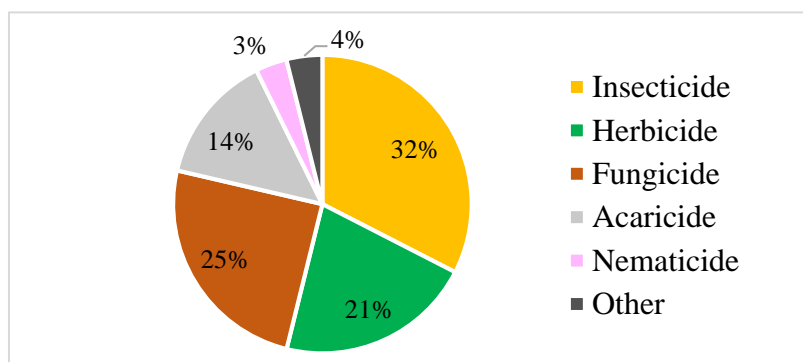
Figure 4.1. *Types of pesticides found in Koh Thum district*
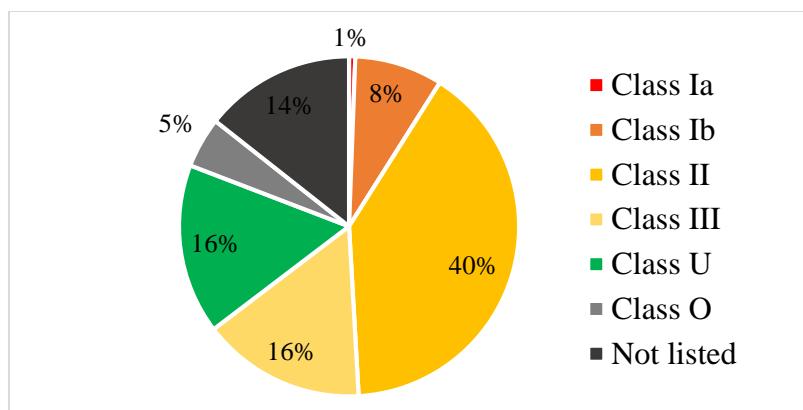
Figure 4.2. *WHO class of pesticides found in Koh Thum district*

Furthermore, among the 37 detectable pesticides on the list comprising 77 pesticides identified from interviews, 21 were detected and 16 were not detected through the GC-MS analysis. Thiacloprid, butachlor, lufenuron and triazole which were highly expected to be found through their high typical persistence in water phase were not detectable because out of the MS database. Fipronil, hexaconazole, paclobutrazol, metolachlor were detected as expected, whereas bentazone was not detected despite its high persistence. In addition, 146 molecules which were not mentioned in the interviews were detected.

4.3. Results of analysis, with regulations

Various pesticide molecules were detected in Koh Thum district through semi-quantitative analysis, including 119 molecules either not approved or not registered in the European Union (European Comission, n.d.), while 10 were banned from Cambodia since 2012 (Preap and Sareth, 2015); namely captafol, captan, azinphos-methyl, aldoxycarb, famphur (see **Appendix C**), metamidophos, o,p'-DDT, isoxathion, dieldrin and endrin (see **Table 4.2**). Moreover, 11 molecules were detected among the 24 targeted pesticides, with low to very low concentrations. Among those 11 molecules, only two were authorized in European Union, namely metalaxyl and mefenofam (metalaxyl-M). Chloroneb and triadimefon were detected in every location. Chloroneb was detected with high concentrations in the mango farm groundwater ($3.4010 \pm 0.3644\,\mu g/L$) and in the water in the middle of the prek ($3.8314 \pm 0.0826\,\mu g/L$); chloroneb was also detected with fairly high concentrations in the water of the drainage gate ($1.1099 \pm 0.1544\,\mu g/L$) and in the Bassac river ($0.9449 \pm 0.8682\,\mu g/L$); chloroneb was detected with moderate concentrations in the water of prek west ($0.4282 \pm 0.0491\,\mu g/L$) and in the rice farm water ($0.5231 \pm 0.0736\,\mu g/L$). Triadimefon was detected with low concentrations

28

in every location: from 0.0158 ± 0.0137 µg/L to 0.0331 ± 0.0119 µg/L. Methamidophos and pyroquilon were detected only in the water in the middle of the prek with very low concentrations (0.0019 ± 0.0032 µg/L and 0.0018 ± 0.0031 µg/L). O,p'-DDT, metalaxyl and mefenoxam (metalaxyl-M) were detected only in the mango farm groundwater with very low to moderate concentrations (0.0029 ± 0.0051 µg/L, 0.2319 ± 0.2452 µg/L and 0.3121 ± 0.3293 µg/L). Isoxathion was detected only in the mango farm groundwater with very low concentration (0.0055 ± 0.0096 µg/L) while endrin was detected only in the water of the drainage gate with very low concentration (0.0114 ± 0.0197 µg/L). Dieldrin and azaconazole were both detected in the rice farm water with very low concentrations (0.0035 ± 0.0061 µg/L and 0.0011 ± 0.0019 µg/L); while dieldrin was detected with very low concentration in the water of drainage gate (0.0278 ± 0.0254 µg/L) and azaconazole was detected with very low concentration in the mango farm groundwater (0.0123 ± 0.0213 µg/L) (see **Table 4.2.**)

Table 4.2. *Target pesticides detected through quantitative analysis*

Pesticide	Concentrations detected at the sample locations					
	Bassac (µg/L)	D. Gate (µg/L)	Mango F (µg/L)	Middle PT (µg/L)	PT West (µg/L)	Rice F (µg/L)
Methamidophos	-	-	-	0.0019 ± 0.0032	-	-
o,p'-DDT	-	-	0.0029 ± 0.0051	-	-	-
Metalaxyl	-	-	0.2319 ± 0.2452	-	-	-
Isoxathion	-	-	-	-	-	0.0055 ± 0.0096
Dieldrin	-	0.0278 ± 0.0254	-	-	-	0.0035 ± 0.0061
Endrin	-	0.0114 ± 0.0197	-	-	-	-
Chloroneb	0.9449 ± 0.8682	1.1099 ± 0.1544	3.4010 ± 0.3644	3.8314 ± 0.0826	0.4282 ± 0.0491	0.5231 ± 0.0736
Pyroquilon	-	-	-	0.0018 ± 0.0031	-	-
Azaconazole	-	-	0.0123 ± 0.0213	-	-	0.0011 ± 0.0019
Mefenoxam	-	-	0.3121 ± 0.3293	-	-	-
Triadimefon	0.0283 ± 0.0184	0.0176 ± 0.0155	0.0158 ± 0.0137	0.0197 ± 0.0134	0.0331 ± 0.0119	0.0225 ± 0.0295

4.4. Distribution of pesticides with regard to their persistence and toxicity

4.4.1. The Bassac river

The sample in which the fewest pesticides were detected was the Bassac river with 54 molecules, and none of them were extremely or highly hazardous; which makes this water the least harmful in this study. This could be explained by the fact that the Bassac river is a larger

body of water, more diluted and potentially carrying pesticides elsewhere. Most of the pesticides detected were moderately hazardous (22 molecules), being mostly lowly persistent in water (10 molecules), thus suggesting a recent use by farmers. In addition, 1 of these moderately hazardous molecules detected had moderate persistence, while 3 had high persistence. 11 slightly hazardous pesticides were also detected, of which 4 were lowly persistent, 1 moderately persistent and 1 highly persistent. However, 11 molecules among the 54 could not display their toxicity hazard since they were not listed in the WHO classification (see **Figure 4.3.**).

4.4.2. The drainage gate

71 pesticides were detected in the water of the drainage gate, but none of them were extremely hazardous. Nevertheless, 4 molecules detected were highly hazardous including 1 with moderate persistence (ethiofencarb), 2 with low persistence (methidathion which was banned in Cambodia and European Union, and carbofuran), and 1 with unknown persistence (dieldrin); involving a possible recent use and also a threat to human health. Most of the pesticides found were moderately hazardous (30 molecules), of which 11 were lowly persistent, 1 moderately persistent, and 5 highly persistent. Moreover, 11 molecules detected were slightly hazardous including 1 with moderate persistence, 1 with low persistence and 2 with high persistence. 10 toxicities of molecules among 71 remained unknown. Thus, this water could be seen as moderately hazardous in this study, and involved the greatest number of molecules having low persistence in water phase (40 molecules); a fairly moderate accumulation of pesticides occurred at this location (see **Figure 4.3.**).

4.4.3. The mango farm (groundwater)

The mango farm groundwater counted 61 molecules including 1 extremely hazardous and banned in Cambodia and in European Union, namely captafol. No highly hazardous pesticides were detected in this water sample and most of molecules detected were moderately hazardous (34 molecules), of which 11 were lowly persistent, 1 moderately persistent and 6 highly persistent. 7 molecules detected were slightly hazardous including 1 with low persistence, 1 with moderate persistence and 2 with high persistence. Finally, 6 pesticides among 61 could not be discussed since their WHO hazard toxicities were unknown.

Consequently, the groundwater did not appear globally as very hazardous, although one extremely toxic pesticide should be taken into consideration (see **Figure 4.3.**).

4.4.4. The middle of the prek

In the water in the middle of the prek, a lot of molecules were detected (86 molecules), including 1 extremely hazardous and banned in Cambodia and in European Union (captafol). Furthermore, this water sample enumerated the highest number of highly hazardous molecules (7 molecules) including 1 lowly persistent (carbofuran), 2 moderately persistent (ethiofencarb and methamidophos), 1 highly persistent (triazofos) and 3 of unknown persistence (dinoseb, isofenphos and dicrotophos). 41 moderately hazardous pesticides were also detected of which 15 had low persistence in water, 2 had moderate persistence and 4 had high persistence. In addition, 13 slightly hazardous pesticides were detected in this sample, which included 2 molecules with low persistence, 2 molecules with moderate persistence and 2 molecules with high persistence. 6 molecules among 86 had unknown toxicity. This water could be evaluated as one of the most hazardous in this study. The water in the middle of the prek was supposed to collect a part of irrigation return flow after pesticide use in the crops, explaining why it was heavily loaded, particularly with highly toxic pesticides (see **Figure 4.3.**)

4.4.5. The west of the prek

At the west of the prek, 57 pesticides were found, which makes this water the second least contaminated. However, captafol (extremely hazardous) was detected in addition to 4 highly hazardous pesticides such as cyfluthrin 2, 3 and 4 (low persistence) and dicrotophos (unknown persistence); announcing a potential threat to humans. 26 moderately hazardous molecules were also detected including 9 with low persistence, 2 moderate persistence and 3 high persistence. 8 slightly hazardous molecules were found of which 2 were lowly persistent, 2 moderately persistent and 1 highly persistent. 8 toxicities of pesticides among 57 remained unknown. This water sample did not incorporate so many pesticides compared to other samples, but did contain a fairly high and concentrated toxicity (see **Figure 4.3**).

4.4.6. The rice field

99 molecules were detected in the water of the rice field, which made this water the most contaminated in this study. This stagnant water was most likely to have been used for rice crop irrigation, and therefore in direct contact with pesticide used by farmers. Captafol (extremely hazardous) was detected, in addition to 5 highly hazardous pesticides including 1 with low persistence (carbofuran) and 4 with unknown persistence namely azinphos-methyl, dieldrin and isoxathion which were banned in European union and in Cambodia, and dicrotophos. Moreover, 42 other molecules classified as moderately hazardous were found including 14 lowly persistent, 4 moderately persistent and 6 highly persistent; revealing a potential problem for ecosystems and human health. 20 slightly hazardous molecules were also detected of which 6 had low persistence in water, had moderate persistence 2 and 3 had high persistence. However, 14 molecules among 99 could not be discussed since they were not listed in WHO classification. Consequently, this water appeared to be the most loaded with pesticides and contained the greatest number of persistent pesticides, thus revealing the most important point of accumulation in this study (see **Figure 4.3**).
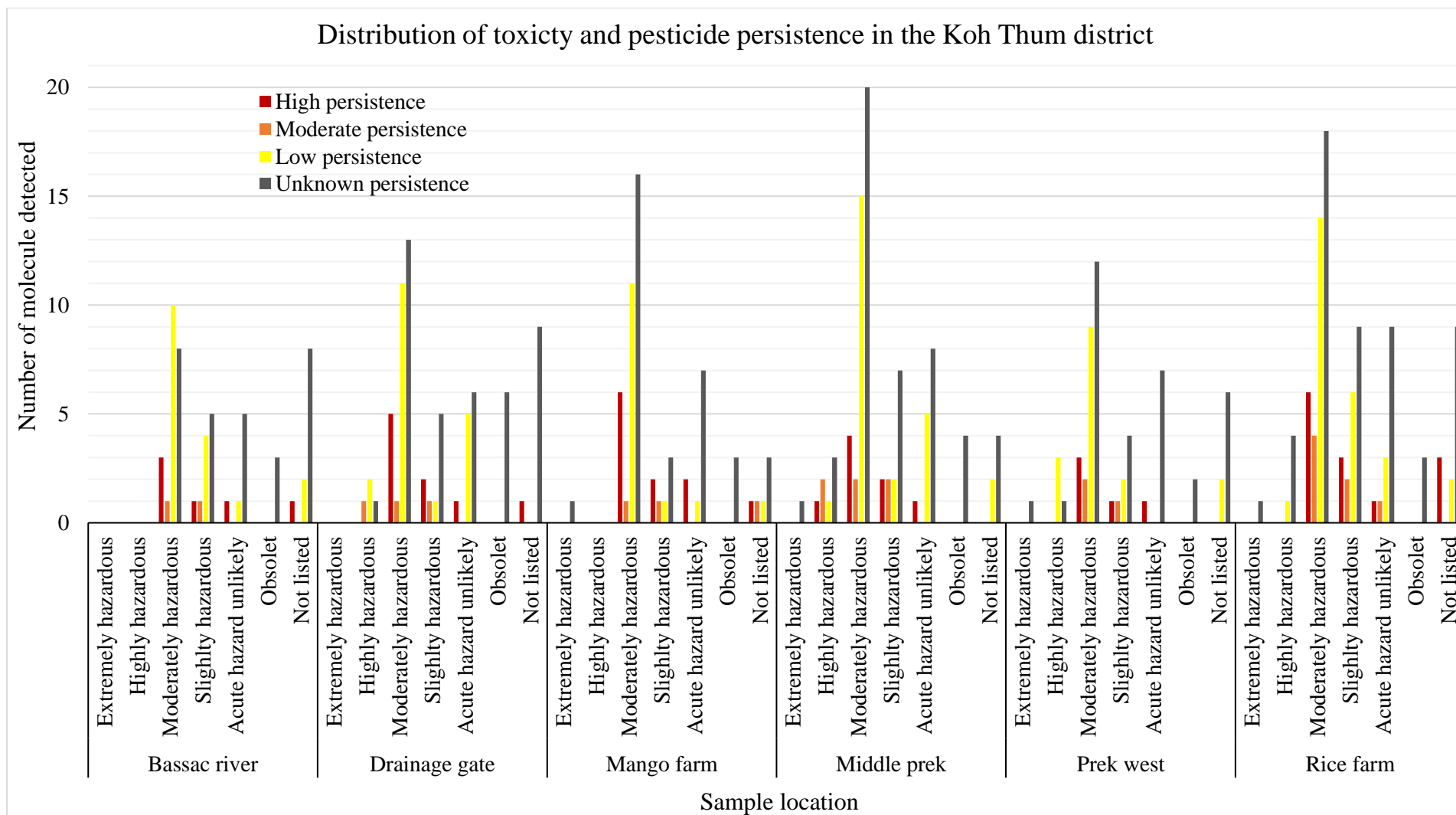
Figure 4.3. *Distribution of toxicity and pesticide persistence in the Koh Thum district*

4.5. Pesticide inter-location transfers

4.5.1. Transfer between the rice crop and the prek

The rice field water counted 48, 50 and 46 molecules in common with west water of the prek, the drainage gate water and the water in the middle of the prek respectively. Thus, the transfer of pesticides between the crop and the prek was quite important and homogeneous in term of number of pesticides. However, many molecules did not displace from the rice field water, moving neither towards the water west of the prek (53 molecules), nor towards the drainage gate water (49 molecules), nor towards the water in the middle of the prek (48 molecules). Conversely, few molecules stayed in the water west of the prek, not moving towards the rice field water (12 molecules). 23 molecules in the drainage gate water and 36 molecules in the water in the middle of the prek did not move to the rice field water. Consequently, many pesticides applied in the crop would move weakly towards the prek water, probably because of the low level of water during the dry season, or because they would degrade faster since lowly persistent molecules were present in majority. Moreover, pesticides contained in the prek water globally seemed to move more easily to the rice field but this should be explained by the fact that farmers used the water from the prek to irrigate the crops, thus accumulating the newly used pesticides with those which would have not yet been degraded and which would remain in the prek water.

4.5.2. Transfer between the prek and the Bassac river

Within a prek channel, the west of the prek communicated directly with the drainage gate, itself communicating with the middle of the prek, which ended to the Bassac river. 34 pesticides were common to the west and the drainage gate waters; however, 25 were detected in the west water but not in the drainage gate water; whereas 37 were detected in the drainage gate water but not in the west water. 41 pesticides were common to the drainage gate water and the water in the middle of the prek; however, 31 pesticides were detected in the drainage gate water but not in the water in the middle of the prek; whereas 43 pesticides were detected in the water in the middle of the prek but not in the drainage gate water. In addition, 34 pesticides were common to the water in the middle of the prek and the Bassac river; however, 49 were detected in the water in the middle of the prek but not in the Bassac river; whereas 20 were detected in the Bassac river but not in the water in the middle of the prek. Most of the pesticides in common and different were lowly persistent but some were highly persistent. Consequently,

during the dry season, majority of pesticides could not move through the different part of the prek and even less to the Bassac river, probably due to the low and heterogeneous levels of water in the prek and also because they may degrade relatively quickly. Some highly persistent molecules may stay over time since they degraded slowly or could eventually move to the groundwater. An accumulation of pesticides would be noticeable towards the water in the middle of the prek rather than at its extremities. Consequently, from this accumulation in the middle of the prek, pesticides would seem to move on the one hand towards the drainage gate then towards the west on the left side, and on the other hand, but less, towards the Bassac river on the right side, the latter carrying pesticides elsewhere than in the prek system.

4.5.3. Transfer towards the groundwater

Firstly, 44 molecules were common to rice field water and mango groundwater; however, 53 molecules were detected in rice field water but not in groundwater, whereas 15 molecules were detected in the groundwater but not in the rice field water. This could mean that many pesticides from the crop could reach the groundwater even if a majority of them still could not because they would degrade before or because they would have a low GUS. Concerning the Bassac river, it shared 32 common molecules with the groundwater, while 22 molecules were detected in the river but not in the groundwater, and 27 molecules were detected in the groundwater but not in the river. The groundwater had 32, 38 and 39 molecules in common with the west water of prek, the drainage gate water and the water in the middle of prek respectively. In addition, 25, 33 and 19 molecules remained in the west water of the prek, the drainage gate water, and the water in the middle of the prek respectively. Thus, the transfer of pesticides from the prek water to the groundwater did not vary much between locations, although more pesticides could move from the water in the middle of the prek Also, more pesticides remained in the drainage gate water than in other prek locations, and less pesticides remained in the water in the middle of the prek than in other prek locations. From the side of the groundwater, 28, 22 and 43 molecules were detected in it, not being present in the west water of the prek, the drainage gate water and the water in the middle of the prek respectively. Finally, many pesticides could move from the different locations to the groundwater; the most came from the water in the middle of the prek, and the less came from the rice farm field water.

5. CONCLUSION

The results of pesticide contamination in the Koh Thum district during the dry season were conclusive and provided useful information. 167 pesticide molecules were detected, including 21 identified in the list drawn-up from interviews and 146 off-list. The three major types of biocides were insecticides, fungicides and herbicides, and most of pesticides were moderately hazardous. 5 chemical families of pesticides were predominant: carbamates, organophosphates, triazoles, organochlorines and pyrethroids. 119 pesticides not authorized in European Union and 10 banned from Cambodia were detected. Moreover, 11 target pesticides among 24 were detected, including 9 not allowed in European Union. Triadimefon and chloroneb were detected in every water sample; triadimefon with very low concentrations but chloroneb from low to high concentration especially in the groundwater and in the water of the middle of the prek. The Bassac river was the least contaminated and the least hazardous water in term of potency of toxicity. However, pesticides accumulated mostly in the rice field water, but also in the water of the middle of the prek, then in the drainage gate water. The water of the middle of the prek was the most hazardous, while captafol which was banned in Cambodia was detected in the groundwater, the rice field water, the west water of the prek and in the water in the middle of the prek. Otherwise, transfers inter-locations appeared complexes, involving pesticide transfers with groundwater in every location, the most from the middle of the prek. Pesticides in water may be transported weakly from the rice field to the prek during the dry season because of the low level of water and the relative fast degradation of pesticides, but more strongly in the opposite way, probably through irrigation by farmers. Pesticides should also be displaced weakly along the prek canal. A certain threat to biodiversity, crop renewal and human health may be present in this agricultural area. On the basis of these conclusions, more focused studies could be carried out. It would be recommended to extend the MS database in order to detect other pesticides such as glyphosate which was largely applied in Kandal. Additional studies should also be carried out in order to obtain more data on the persistence, toxicities and behavior of pesticides in environments, particularly for newly introduced molecules.

REFERENCES

Adeshina, Y.A., Solomon, A., Ademola, A.F., 2019. Contamination Levels of Organochlorine and Organophosphorous Pesticide Residues in Water and Sediment from River Owena, Nigeria. Curr. J. Appl. Sci. Technol. 34, 11.
https://doi.org/10.9734/cjast/2019/v34i230119

Aktar, W., Sengupta, D., Chowdhury, A., 2009. Impact of pesticides use in agriculture: their benefits and hazards. Interdiscip. Toxicol. 2, 12. https://doi.org/10.2478/v10102-009-0001-7

Alavanja, M.C.R., 2009. Pesticides Use and Exposure Extensive Worldwide. Rev. Environ. Health 24, 303–309.
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2946087/?mc_cid=c1c3bd26b6&mc_eid=15aad5049c&utm_campaign=c1c3bd26b6-EMAIL_CAMPAIGN_2018_10_08_01_54&utm_medium=email&utm_source=Body Health+Maillings&utm_term=0_8d00b7736f-c1c3bd26b6-18121477

Alves, A.A.R., Rezende, M.J.C., Hovell, A.M.C., Bizzo, H.R., Oliveira, A.C.L., Rodrigues, S.V., Rezende, C.M., 2012. Comparison between GC-MS-SIM and GC-ECD for the determination of residues of organochlorine and organophosphorus pesticides in Brazilian citrus essential oils. J. Braz. Chem. Soc. 23, 306–314.
https://doi.org/10.1590/S0103-50532012000200017

Arisekar, U., Shakila, R.J., Jeyasekaran, G., Shalini, R., Kumar, P., Malani, A.H., Rani, V., 2019. Accumulation of organochlorine and pyrethroid pesticide residues in fish, water, and sediments in the Thamirabarani river system of southern peninsular India. Environ. Nanotechnol. Monit. Manag. 11, 1–13. https://doi.org/10.1016/j.enmm.2018.11.003

Barakat, A.O., Khairy, M., Aukaily, I., 2013. Persistent organochlorine pesticide and PCB residues in surface sediments of Lake Qarun, a protected area of Egypt. Chemosphere 90, 2467–2476. https://doi.org/10.1016/j.chemosphere.2012.11.012

Carvalho, F.P., 2017. Pesticides, environment, and food safety. Food Energy Secur. 6, 48–60. https://doi.org/10.1002/fes3.108

Darko, G., Akoto, O., Oppong, C., 2008. Persistent organochlorine pesticide residues in fish, sediments and water from Lake Bosomtwi, Ghana. Chemosphere 72, 21–24. https://doi.org/10.1016/j.chemosphere.2008.02.052

European Comission, n.d. EU Pesticides database [WWW Document]. URL https://ec.europa.eu/food/plant/pesticides/eu-pesticides-database/public/?event=activesubstance.selection&language=EN (accessed 3.6.20).

Food and Agriculture Organization of the United Nations (FAO), 2018. FAOSTAT [WWW Document]. URL http://www.fao.org/faostat/en/#data/EP/visualize (accessed 2.10.20).

Hoffman, D.J., Rattner, B.A., Jr, G.A.B., Jr, J.C., 2002. Handbook of Ecotoxicology. CRC Press.

Hussain, S.Z., Maqbool, K., 2014. GC-MS: Principle, Technique and its application in Food Science. International Journal of Current Science., pp. 116–126.

Idowu, S.O., Capaldi, N., Zu, L., Gupta, A.D. (Eds.), 2013. Stockholm Convention on Persistent Organic Pollutants (POPs), in: Stockholm Convention on Persistent Organic Pollutants (POPs). Springer Berlin Heidelberg, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-28036-8_101506

Jayaraj, R., Megha, P., Sreedev, P., 2016. Organochlorine pesticides, their toxic effects on living organisms and their fate in the environment. Interdiscip. Toxicol. 9, 90–100.

Jin, X., Liu, Y., Qiao, X., Guo, R., Liu, C., Wang, X., Zhao, X., 2019. Risk assessment of organochlorine pesticides in drinking water source of the Yangtze River. Ecotoxicol. Environ. Saf. 182, 6. https://doi.org/10.1016/j.ecoenv.2019.109390

Jinya, D., 2013. Development of Solid-Phase Extraction Method for Simultaneous Analysis of Semi-Volatile Organic Compounds Using a GC-MS Database System. Shimadzu Corp. C146-E202, 8.

Kafilzadeh, F., 2015. Assessment of Organochlorine Pesticide Residues in Water, Sediments and Fish from Lake Tashk, Iran. Achiev. Life Sci. 9, 107–111. https://doi.org/10.1016/j.als.2015.12.003

Kangwon National University, 2011. Evaluation of Pesticide Residues in Soil, Evaluation of residual pesticide risk in the soil. ed.

Kaur, R., Mavi, G.K., Raghav, S., Khan, I., 2019. Pesticides Classification and its Impact on Environment. Int. J. Curr. Microbiol. Appl. Sci. 8, 1889–1897. https://doi.org/10.20546/ijcmas.2019.803.224

Keo, S., 2019. Analysis of pesticide residues in surface water in Chhnok Trou community of Tonle Sap Lake during low water season. Institute of Technology of Cambodia, Phnom Penh.

Kingdom of Cambodia, 2004. Drinking water Quality Standards. Ministry of Industry Mines and Energy, Cambodia.

Kutz, F.W., Wood, P.H., Bottimore, D.P., 1991. Organochlorine Pesticides and Polychlorinated Biphenyls in Human Adipose Tissue*, in: Ware, G.W. (Ed.), Reviews of Environmental Contamination and Toxicology, Reviews of Environmental Contamination and Toxicology. Springer, New York, NY, pp. 1–82. https://doi.org/10.1007/978-1-4612-3080-9_1

Kwong, T.C., 2002. Organophosphate Pesticides: Biochemistry and Clinical Toxicology. Ther. Drug Monit. 24, 144–149.

Liu, J., Qi, S., Yao, J., Yang, D., Xing, X., Liu, H., Qu, C., 2016. Contamination characteristics of organochlorine pesticides in multimatrix sampling of the Hanjiang River Basin, southeast China. Chemosphere 163, 35–43. https://doi.org/10.1016/j.chemosphere.2016.07.040

Matsukawa, M., Ito, K., Kawakita, K., Tanaka, T., 2016. Current status of pesticide use among rice farmers in Cambodia. Appl. Entomol. Zool. 51, 571–579. https://doi.org/10.1007/s13355-016-0432-5

Mekong River Commission (Ed.), 2010. State of the basin report 2010. Mekong River Commission, Vientiane.

Northern Ireland Environment Agency, 2011. European and National Drinking Water Quality Standards.

NPIC, n.d. National Pesticide Information Center - Home Page [WWW Document]. URL http://npic.orst.edu/ (accessed 3.2.20).

Ntow, W.J., 2005. Pesticide residues in Volta Lake, Ghana. Lakes Reserv. Res. Manag. 10, 243–248. https://doi.org/10.1111/j.1440-1770.2005.00278.x

Pratx, O., 2017. Etude du fonctionnement hydro-agricole de canaux d'irrigation: Cas des « preks » sur les rives du Bassac au Cambodge. ENGEES, Institut de Recherche pour le Développement - UMR G-EAU.

Preap, V., Sareth, K., 2015. Current Use of Pesticides in the Agricultural Products of Cambodia. Gen. Dir. Agric. GDA Minist. Agric. For. Fish. MAFF Kingd. Cambodia 9.

PubChem, n.d. U.S. National Library of Medecine [WWW Document]. URL https://pubchem.ncbi.nlm.nih.gov/ (accessed 3.2.20).

Rathore, H.S., Nollet, L.M.L., 2012. Pesticides: Evaluation of Environmental Pollution. CRC Press.

Rifai, A., 2013. Etude de la dégradation par photolyse directe de pesticides - Caractérisation structurale et toxicité potentielle des photoproduits (phdthesis). Ecole Polytechnique X.

Samsidar, A., Siddiquee, S., Shaarani, S.M., 2018. A review of extraction, analytical and advanced methods for determination of pesticides in environment and foodstuffs. Trends Food Sci. Technol. 71, 188–201. https://doi.org/10.1016/j.tifs.2017.11.011

Schreinemachers, P., Afari-Sefa, V., Heng, C., Dung, P., Praneetvatakul, S., Ramasamy, S., 2015. Safe and sustainable crop protection in Southeast Asia: Status, challenges and policy options. Environ. Sci. Policy 54, 357–366. https://doi.org/10.1016/j.envsci.2015.07.017

Tran, T.A.M., Malarvannan, G., Hoang, T.L., Nguyen, V.H., Covaci, A., Elskens, M., 2019. Occurrence of organochlorine pesticides and polychlorinated biphenyls in sediment and fish in Cau Hai lagoon of Central Vietnam: Human health risk assessment. Mar. Pollut. Bull. 141, 521–528. https://doi.org/10.1016/j.marpolbul.2019.03.006

University of Hertfordshire, n.d. PPDB - Pesticides Properties DataBase [WWW Document]. URL https://sitem.herts.ac.uk/aeru/ppdb/ (accessed 3.2.20).

Uqab, B., Mudasir, S., Nazir, R., 2016. Review on Bioremediation of Pesticides. J. Bioremediation Biodegrad. 7, 5. https://doi.org/10.4172/2155-6199.1000343

US Environmental Protection Agency (US EPA), O., 2013. Impact Reports and Fact Sheets [WWW Document]. US EPA. URL https://www.epa.gov/research/impact-reports-and-fact-sheets (accessed 3.2.20).

US EPA, 2018. Edition of the drinking water standards and health advisories tables.

Wang, H.-S., Sthiannopkao, S., Du, J., Chen, Z.-J., Kim, K.-W., Mohamed Yasin, M.S., Hashim, J.H., Wong, C.K.-C., Wong, M.-H., 2011. Daily intake and human risk assessment of organochlorine pesticides (OCPs) based on Cambodian market basket data. J. Hazard. Mater. 192, 1441–1449. https://doi.org/10.1016/j.jhazmat.2011.06.062

Wilson, C., Tisdell, C., 2001. Why farmers continue to use pesticides despite environmental, health and sustainability costs. Ecol. Econ. 39, 449–462. https://doi.org/10.1016/S0921-8009(01)00238-5

World Health Organization (WHO), 2018. Guidelines for drinking-water quality: fourth edition incorporating the first addendum, 4th ed. WHO Library Cataloguing-in-Publication Data.

World Health Organization (WHO), 2010. The WHO recommended classification of pesticides by hazard and guidelines to classification 2009. World Health Organization.

World Health Organization (WHO), 2008. Pesticides, Children's Health and the Environment.

World Health Organization (WHO), n.d. World Health Organization [WWW Document]. URL https://www.who.int (accessed 4.6.20).

Zhang, W., 2018. Global pesticide use: Profile, trend, cost / benefit and more. Proc. Int. Acad. Ecol. Environ. Sci. 8, 27.

Zhao, X., Cui, T., Guo, R., Liu, Y., Wang, X., An, Y., Qiao, X., Zheng, B., 2019. A clean-up method for determination of multi-classes of persistent organic pollutants in sediment and biota samples with an aliquot sample. Anal. Chim. Acta 1047, 71–80. https://doi.org/10.1016/j.aca.2018.10.011

Żwir-Ferenc, A., Biziuk, M., 2006. Solid Phase Extraction Technique – Trends, Opportunities and Applications. Pol. J. Environ. Stud. 15, 677–690.

APPENDICES

Appendix A: Drinking water standards

Table A1. *WHO water drinking standard*

Chemical	WHO Guideline Value (µg/L)
Alachlor	20
Aldicarb	10
Aldrin and dieldrin	0.03
Atrazine and its chloro-s-triazine metabolites	100
Carbofuran	7
Chlordane	0.2
Chlorotoluron	30
Chlorpyrifos	30
Cyanazine	0.6
2,4-Dichlorophenoxyacetic acid	30
2,4-Dichlorophenoxybutyric acid	90
1,2-Dibromo-3-chloropropane	1
1,2-Dibromoethane	0.4
1,2-Dichloropropane	40
1,3-Dichloropropene	20
Dichlorprop	10
Dimethoate	6
Endrin	0.6
Fenoprop	9
Hydroxyatrazine	200
Isoproturon	8
Lindane	2
Mecoprop	10
Methoxychlor	20
Metolachlor	10
Molinate	6
Pendimethalin	20
Simazine	2
2,4,5-Trichlorophenoxyacetic acid	9
Terbuthylazine	7
Trifluralin	20

Table A2. *US EPA drinking water standard*

Chemical	US EPA Guideline Value (µg/L)
Alachlor	2
Aldicarb	3
Atrazine	3
Bromodichloromethane	80
Bromoform	80
Carbofuran	40
Carbon tetrachloride	5
Chlordane	2
Chloroform	80
2,4-dichlorophenoxyacetic acid	70
Dalapon	200
Dibromochloromethane	80

Table A2. *US EPA drinking water standard (continued)*

Dibromochloropropane	0.2
Dichloroacetic acid	60
Dichlorobenzene o-	600
Dichlorobenzene p-	75
Dichloroethane (1,2-)	5
Dichloroethylene (1,1-)	7
Dichloroethylene (cis-1,2-)	70
Dichloroethylene (trans-1,2-)	100
Dichloromethane	5
Dichloropropane (1,2-)	5
Dinoseb	7
Diquat	20
Endothall	100
Endrin	2
Ethylbenzene	700
Ethylene dibromide	0.05
Glyphosate	700
Heptachlor	0.4
Heptachlor epoxide	0.2
Hexachlorobenzene	1
Hexachlorocyclopentadiene	50
Lindane	0.2
Methoxychlor	40
Monochloroacetic acid	60
Monochlorobenzene	100
Oxamyl (Vydate)	200
Pentachlorophenol	1
Picloram	500
Polychlorinated biphenyls	0.5
Simazine	4
Tetrachloroethylene	5
Toxaphene	3
2,4,5-TP (Silvex)	50
Trichloroacetic acid	60
Trichlorobenzene (1,2,4-)	70
Trichloroethane (1,1,1-)	200
Trichloroethane (1,1,2-)	5
Trichloroethylene	5
Vinyl chloride	2

Table A3. *Cambodian drinking water standard*

Chemical	Guideline Value (µg/L)
Polychlorinated biphenyls	0.5
Benzene	10
2,4-dichlorophenoxyacetic acid	30
Aldrin and Dieldrin	0.3
Carbofuran	10
Chlordane	0.2
DDT	20
Dichlorvos	1
Dirnethoate	6
Endosulfan	30

Table A3. *Cambodia drinking water standard (continued)*

Endrin	0.6
Glyphosate	10
Heptachlor	0.3
Hexachlorobenzene	1
Methyl parathion	5
Mevinphos	1
Monocrotophos	30
Paraquat	10
Parathion	20

Appendix B: Photography of experiment

Figure B1. Sample collection and filtration of Bassac river water

Figures B2. SPE: Sample Elution & PLS3 Sorbent Washing

Figure B3. The 18 water samples and the 6 standards solution, ready for analysis

Appendix C: Results of semi-quantitative analysis for pesticides detected in Koh Thum (see below)

Table C.1. *Pesticide molecules detected in Koh Thum district*

	Molecule	Ethiofencarb	Dicofol	Dicofol (deg)	Captafol	Acephate	Triflumizole	Methoprene	Pyridate	Terbucarb (MBPMC)	Bensulide	Methyldymron	Captan	Isoprothiolane	Triclopyr	Dinoseb
Location	Bassac	-	-	-	-	-	-	+	+	+	++	+	-	-	+	-
	D. Gate	+	-	+	-	-	-	+	-	-	++	-	-	-	+	-
	Mango F	-	-	-	+	+	-	+	-	-	++	+	-	-	+	+
	Middle PT	+	-	+	+	-	+	+	-	+	++	-	+	+	+	-
	PT West	-	+	+	+	-	-	+	+	+	++	+	-	-	+	-
	Rice F	-	-	-	+	-	-	+	+	+	+	+	+	+	+	-
Authorization EU		No	No	No	No	No	No	No	Yes	/	No	/	Yes	No	Yes	No
Authorization KH		/	/	/	No	/	/	/	/	/	/	/	No	/	/	/

	Molecule	Dimethametryn	Carboxin	Diclofop methyl	Pebulate	Molinate	Cycloate	Metribuzin	Metribuzin DADK	Metribuzin DK	Metribuzin DA	Isoprocarb	Bromobutide	Methidathion	Buprofezin
Location	Bassac	++	-	+	+	+	-	-	+	+	+	-	-	-	-
	D. Gate	++	-	++	+	+	+	-	+	+	+	+	+	+	-
	Mango F	+	-	-	+	+	+	+	+	+	+	+	-	-	-
	Middle PT	++	-	-	+	+	-	+	+	+	+	+	-	-	-
	PT West	++	-	+	+	+	-	+	+	+	-	+	+	-	-
	Rice F	+	+	++	+	+	+	-	+	+	+	-	+	-	+
Authorization EU		/	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes	No	/	No	Yes
Authorization KH		/	/	/	/	/	/	/	/	/	/	/	/	/	/

	Molecule	Propham	XMC	Propachlor	Propanil	Oxadixyl	Propargite 2	Pyrazophos	Ametryn	Bromacil	Fenpropimorph	Allethrin 1	Allethrin 2 & Bioallethrin 1	Metominostrobin E	Ethion
Location	Bassac	-	-	-	-	-	-	-	-	-	+	+	+	-	-
	D. Gate	-	+	+	-	-	-	-	-	-	-	-	+	-	-
	Mango F	+	+	-	-	-	-	-	-	-	-	+	-	-	-
	Middle PT	-	-	-	+	+	+	-	-	-	-	+	+	-	+
	PT West	-	-	-	-	+	-	-	-	+	-	-	-	-	-
	Rice F	-	+	-	-	+	-	+	+	-	-	+	-	+	-
Authorization EU		No	No	No	No	No	No	No	No	No	No	No	No	No	No
Authorization KH		/	/	/	/	/	/	/	/	/	/	/	/	/	/

	Molecule	Hexazinone	Fenoxycarb	6-Benzylaminopurine	Azinphos-methyl	Fluquinconazole	Fenbuconazole	Flamprop-methyl	Fenoxanil	Hymexazol	Fluazinam	Imazamethabenz methyl	Nitralin
Location	Bassac	+	-	-	-	-	-	+	+	+	-	-	-
	D. Gate	+	+	-	-	-	-	+	-	+	-	+	-
	Mango F	+	-	+	-	-	-	+	-	+	-	-	+
	Middle PT	-	-	-	-	-	-	+	-	+	-	-	+
	PT West	+	-	-	-	++	-	+	-	+	-	-	-
	Rice F	+	-	-	+	-	+	+	-	+	-	-	-
Authorization EU		No	Yes	Yes	No	Yes	Yes	No	/	Yes	Yes	No	No
Authorization KH		/	/	/	No	/	/	/	/	/	/	/	/

Table C.1. *Pesticide molecules detected in Koh Thum district (continue)*

Molecule		Triazophos	Spirodiclofen	*(lambda)* Cyhalothrin 1	*(gamma)* Cyhalothrin 2	o,p'-DDD	Benfuresate	Butachlor	Cinmethylin	Chlorobenzilate	Pyriproxyfen	Mefenacet	Pendimethalin
	Bassac	-	+	+	+	-	+	-	+	-	+	-	-
	D. Gate	-	-	-	-	+	+	-	+	+	+	-	-
Location	Mango F	-	-	+	-	+	-	-	+	-	-	+	-
	Middle PT	+	-	-	+	+	-	+	+	-	-	-	-
	PT West	-	+++	-	-	-	-	+	+	-	-	-	-
	Rice F	-	+++	+	-	-	+	++	+	-	-	+	+
Authorization EU		No	No	Yes	Yes	/	No	No	/	No	Yes	No	Yes
Authorization KH		/	/	/	/	/	/	/	/	/	/	/	/

Molecule		Propiconazole 1	Propiconazole 2	Tebuconazole	Alachlor	Chlorfenapyr	Cyfluthrin 2	Cyfluthrin 3	Cyfluthrin 4	Cyproconazole	Cyprodinil	Isofenphos	Permethrin 1	Permethrin 2
	Bassac	-	-	+	-	+	-	-	-	+	+	-	-	-
	D. Gate	-	-	+	-	+	-	-	-	+	-	-	-	-
Location	Mango F	+	+	+	-	+	-	-	-	+	-	-	-	-
	Middle PT	+	+	+	+	+	-	-	-	+	-	+	-	-
	PT West	-	-	+	+	+	+	+	+	+	-	-	-	-
	Rice F	-	-	+	+	+	-	-	-	+	+	-	+	+
Authorization EU		No	No	Yes	No	No	No	No	No	Yes	Yes	No	No	No
Authorization KH		/	/	/	/	/	/	/	/	/	/	/	/	/

Molecule		Lenacil	Metolachlor	Iprobenfos (IBP)	Mepanipyrim	Mepronil	Myclobutanil	Fenitrothion (MEP)	Fluvalinate 1	Fluvalinate 2	Etobenzanid	Fludioxonil	Kresoxim methyl	Fenpropathrin
	Bassac	-	-	-	-	+	-	+	-	-	+	-	-	+
	D. Gate	-	-	+	+	+	+	+	-	-	-	-	-	+
Location	Mango F	+	-	+	-	+	+	-	-	-	-	-	-	+
	Middle PT	-	-	-	-	+	+	-	-	-	-	+	+	+
	PT West	-	-	-	-	+	+	-	-	-	+	-	-	++
	Rice F	+	+	+	+	+	-	-	+	+	+	-	+	+
Authorization EU		Yes	No	No	Yes	No	Yes	No	Yes	Yes	/	Yes	Yes	No
Authorization KH		/	/	/	/	/	/	/	/	/	/	/	/	/

Molecule		Triadimenol 2	Paclobutrazol	Uniconazole P	Fenobucarb	Esprocarb	Fosthiazate 1	Fosthiazate 2	Pyridaben	Quinalphos	Pretilachlor	Procymidone	Acetamiprid	EPTC
	Bassac	+	-	-	-	-	+	-	++	-	-	-	-	-
	D. Gate	+	+	+	-	-	+	-	-	-	-	+	-	-
Location	Mango F	+	+	-	+	-	+	+	-	-	-	-	+	-
	Middle PT	+	+	-	+	+	-	+	-	+	+	-	+	-
	PT West	++	-	-	-	-	-	+	++	-	+	-	+	-
	Rice F	++	+	-	+	-	+	+	++	-	++	-	+	+
Authorization EU		No	Yes	No	No	No	Yes	Yes	Yes	No	No	No	Yes	No
Authorization KH		/	/	/	/	/	/	/	/	/	/	/	/	/

Table C.1. *Pesticide molecules detected in Koh Thum district (continue)*

Molecule		Pyrethrin 1	Pyrethrin 2	Pyrethrin 3	Pyrethrin 4	Pencycuron	Trichlamid	Simetryn	Thenylchlor	Tribenuron methyl	Tricyclazole	Aldoxycarb (deg)	3-Hydroxy carbofuran 1	3-Hydroxy carbofuran 2
Location	Bassac	+	-	+	-	-	+	-	-	+	-	+	-	-
	D. Gate	+	+	++	-	-	-	-	+	+	+	+	+	-
	Mango F	-	-	+	+	-	-	-	-	+	-	+	-	+
	Middle PT	+	-	+	+	+	-	+	-	+	-	+	-	-
	PT West	-	-	+	-	-	-	-	+	+	-	+	-	-
	Rice F	+	+	++	-	-	-	+	-	+	+	+	+	+
Authorization EU / KH		Yes	Yes	Yes	Yes	Yes	/	/	/	Yes	No	/	/	/
EU drinking std (µg/L)		/	/	/	/	/	/	/	/	/	/	No	/	/

Molecule		Famphur	Piperonyl butoxide	Prochloraz	Pyrazoxyfen	TCMTB	Difenzoquat metilsulfate	Isoxadifen ethyl	Simeconazole	Clomeprop	Dicrotophos	Cyanofenphos	Biphenyl	Thiocyclam	Oxabetrinil
Location	Bassac	-	-	+	-	+	-	-	-	-	-	-	-	+	+
	D. Gate	+	+	-	-	-	-	-	+	-	-	-	-	+	+
	Mango F	-	-	-	-	-	-	-	-	-	-	-	-	+	-
	Middle PT	-	-	-	-	+	+	+	-	-	+	-	+	+	+
	PT West	-	-	+	+	-	-	-	-	-	+	-	-	+	-
	Rice F	-	+	+	-	-	+	+	-	+	+	+	-	+	-
Authorization EU / KH		/	/	Yes	No	No	No	/	No	No	No	/	No	No	/
EU drinking std (µg/L)		No	/	/	/	/	/	/	/	/	/	/	/	/	/

Molecule		Tetramethrin 1	Tetramethrin 2	Bromuconazole 1	Xylylcarb	Oxpoconazole-formyl	Carbetamide	Thiamethoxam (deg)	Dialifos	Oxpoconazole-fumalate	Prohydrojasmon	Propamocarb	Pentoxazone
Location	Bassac	-	-	-	-	-	-	-	-	+	+	+	-
	D. Gate	-	-	-	-	+	+	-	-	-	+	+	+
	Mango F	-	+	-	-	-	-	-	-	-	+	-	-
	Middle PT	+	+	+	+	-	+	-	+	-	+	+	-
	PT West	-	-	-	+	-	-	-	-	++	+	-	-
	Rice F	-	-	-	+	-	-	+	-	++	+	-	+
Authorization EU / KH		No	No	Yes	/	No	Yes	No	No	No	No	Yes	No
EU drinking std (µg/L)		/	/	/	/	/	/	/	/	/	/	/	/

Molecule		Triadimenol 1	Propoxur	Cyromazine	Tribufos	Phosalone	Fipronil	Phosmet	Benalaxyl	Carbaryl	Carbofuran	Bitertanol	Imazalil	Hexaconazole	Bendiocarb	MCPB ethyl
Location	Bassac	+	-	+	+	-	-	-	+	-	-	-	-	-	+	-
	D. Gate	+	-	+	+	-	+	-	-	+	-	+	+	-	+	-
	Mango F	+	-	+	+	+	-	-	-	-	-	+	+	-	+	-
	Middle PT	+	+	+	-	-	-	+	-	+	-	+	+	+	+	-
	PT West	+	-	+	-	-	+	-	-	-	-	-	-	+	+	-
	Rice F	+	-	+	+	+	+	-	-	+	+	+	+	-	+	+
Authorization EU / KH		No	No	No	No	No	No	Yes	Yes	No	No	No	Yes	No	No	Yes
EU drinking std (µg/L)		/	/	/	/	/	/	/	/	/	/	/	/	/	/	/