THE EFFECTS OF A FOREST FIRE ON WATER FLOW AND QUALITY IN LAKES SURROUNDING A NORTHERN ONTARIO MINE

by

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ABSTRACT

Kinch-McCrae, M. 2022. The effects of a forest fires on water flow and quality in lakes surrounding a Northern Ontario mine

Water quality and quantity can be greatly impacted following a forest fire, but fire impacts can vary based on fire intensity, watershed topography, and post-fire precipitation events. Forest fires are an important contributor to the natural regeneration of forests. Watershed monitoring is important for gaining a greater understanding of forest fire impacts on water resources, thus helping to improve interpretations of overall fire effects. The aim of this study was to reveal fire disturbance impacts on water quality characteristics surrounding a mine site. The forest fire likely resulted in increases in dissolved organic carbon and ammonia concentrations, especially downstream of the mine site. However, no increased metal concentrations occurred after the fire. Increased flows and frequency of peak flow events in the watershed following the fire did occur, which can impact water quality in ways that were not measured.

Key words: boreal forest, fire, mining, watershed monitoring.

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INTRODUCTION

In Canada, a forest fire season occurs every summer, with extended dry and hot weather conditions often amplifying and intensifying fires. The National Forestry Database of Canada reports more than 8000 forest fires in the country each year, burning an average of 2 million hectares of forestland (Canadian National Fire Database 2021). There were over 4700 forest fires in Canada during 2011, with over 1300 occurring within Ontario. The Boreal forest covers two thirds of Ontario's forestland (Government of Ontario 2021) and contains over 1.5 million lakes, accounting for more surface freshwater than any other ecosystem on the globe (Cousins 2021). Natural disturbances, such as wildfires, are common in the Boreal forest. However, Canada's temperatures have been rising over the past 25 years, with nine out of the ten warmest years having occurred since 1997 and the annual average temperature in Canada having increased at roughly twice the global mean rate (Government of Canada 2022). The year of 2021 experienced a national average temperature of 2.1˚C above the reference value, resulting in 2021 having been the fifth warmest year in Canada since 1948, with the summer of 2021 having set record temperatures across North America (Government of Canada 2022).With rising temperatures and changing climate, forest fires have continued and intensified, resulting in devasting environmental consequences in some regions. These fires may have major environmental impacts including air pollution, massively changed ecosystems, large emissions of carbon dioxide, and water pollution. The environmental effects of wildfires on water resources, including water quantity and quality, can vary depending on many factors, including the size and intensity of the fire, the topography of the watershed, the local ecology, and the amount of precipitation following the fire.

Wildfires are a part of nature and are considered natural in modelling and influencing forests and ecosystems, as they serve as an aid to regeneration. On the other hand, forest fires can be particularly damaging as they can result in significantly large-scale damage and impacts, including affecting the quantity and quality of the water and water resources within the fire region. From July through October of 2011, prolonged dry weather conditions and strong winds led to over 140 000 square kilometers of forestland being damaged by forest fires in Northwestern Ontario. Early spring thaw and extended drought throughout Northwestern Ontario allowed fires to grow quickly. One wildfire was so severe it resulted in a forced closure and evacuation of a mine located in the region. After reopening, staff at the mine continued to collect data from the various lakes surrounding the mine site in order to determine how the forest fire may have impacted the water quality characteristics of the various surrounding lakes. The 2011 wildfire allowed an opportunity to compare the impacts and effects on water flow and quality characteristics surrounding a mine site. Water quality data include dissolved organic carbon (DOC), total phosphorus, nitrogen, and cations including iron, mercury, and ammonium compounds.

The overall objective in this thesis is to evaluate the effects of the 2011 forest fire by comparing pre and post fire water quality data from upstream and downstream of the fire in order to determine the effects of wildfires on water properties. Based on previous studies, dissolved organic carbon (DOC) load will have increased following the fire, along with an increase in anions and total nitrogen concentrations, especially downstream of the fire. Additionally, cation concentrations are likely to have increased with an increased flow of water through the mine site after the fire.

LITERATURE REVIEW

WILDFIRE IMPACTS ON FOREST STRUCTURE AND HYDROLOGIC CYCLES

Wildfires are important disturbances in the Boreal Shield and Boreal Forests ecoregions. Following a fire, disturbance can lead to several alterations of forest structure, as well as the hydrologic cycle within the fire burned area. Wildfires can result in increases in annual runoff as a result of loss of forest cover and reduced evapotranspiration (Lamontagne et al., 2000), with high runoff persisting for decades after forest clearance of a fire (Carignan et al., 2000). Wildfires often result in increases of element export rates from drainage areas into lakes and other waterbodies (Lamontagne et al., 2000).

Another major influence of wildfires is increase to water yield and peak flows, as fires create hydrophobic conditions within soils, often resulting in infiltration rates decreased and overland flows increased; however, extremely high intensity fires can actually burn tree roots resulting in rapid infiltration (Putz et al., 2003). As an example, five years postfire in the case of an Alberta fire a 20-220% higher mean annual water yield and peak flows in burned watersheds continued to occur, with fire impacting the water quality as the fire modified the hydrology of the watersheds (Pacheco et al., 2021).

Although riparian areas generally burn less often and less intense compared to their upland forest counterparts, due to the proximity of fire to these natural breaks and their high soil moisture, changes to these areas and their dynamics can be significant (Luke et al., 2007). Since the establishment of the Sustainable Forest Management Network (SFMN) in 1995, there has been a great focus on boreal lake responses to watershed disturbances (Pinel-Alloul et al., 2002).

DISSOLVED ORGANIC CARBON (DOC)

DOC Explained

Dissolved organic carbon (DOC) is created through the decay of organic matter and/or plant exudates and can be identified as the organic matter that passes through a filter, typically 0.45 µm in size (Davidson et al., 2019). DOC is a significant parameter related to water quality and chemistry as it contributes to essential functions in several limnological variables (Williamson et al., 1999). In particular, alterations of DOC have significant implications for other water quality measures in Boreal Shield lakes (Lamontagne et al., 2000). In surface waters, DOC is a recognized measure of natural organic matter with concentrations in waterbodies differing spatially based on the geophysical features of the catchments (Cool et al., 2014). These geophysical features include slope, forest cover, and the presence of wetlands or peatlands, as well as climatic conditions including runoff, precipitation, and storm events. Wildfires can impact DOC concentrations in rivers and lakes including an increase in the export of DOC following the disturbance (Lamontagne et al., 2000).

DOC as a Water Quality Parameter

Impacts of wildfires can vary based on location. DOC generally increases in lakes affected by wildfires (Putz et al., 2003). For example, DOC was 1.5-fold higher in lakes within a Canadian Shield area that was burnt compared to reference lakes (Garcia et al., 2005). Mean DOC increased nearly double, 32.2 to 60.7 mg/L, during the summer months of May to July one year post-fire in a Boreal Forest fen area (Davidson et al., 2019).

Reasoning around Variations in DOC

The outcome of wildfire disturbances can include major changes to the physical structure and hydrologic elements within the disturbed area, subsequently causing variations in water quality parameters, including DOC. Hydrogeological conditions on the Canadian Shield during periods of high runoff have been associated with increases in DOC export from forest soils to surface waters (D'Arcy and Carignan, 1997). DOC levels can be altered as a result of changes in annual runoff following the loss of forest cover (Carignan et al., 2000). Increased DOC export can persist for years following a fire, because high runoff rates can also persist for years.

The changes and removal of vegetation associated with fires in Boreal regions result in an increased groundwater table as evapotranspiration decrease, ultimately causing increases in DOC (Lamontagne et al., 2000). The rise of DOC in waterways can be explained by the heightened water table along with lessened evapotranspiration rates resulting in a greater amount of runoff bypassing the DOC and absorbing mineral soil. Additionally, the raising of a water table can contribute to the development of new flow paths through organic soil layers, ultimately enhancing DOC transport from terrestrial systems into aquatic systems (Putz et al., 2003). Furthermore, enhanced runoff can increase the transfer of terrestrial DOC into waterways through the growth of superficial flow paths through organic soil layers (Carignan et al., 2000). The rapid increase in DOC during the summer months in much of the Boreal region may be attributed to an increase in plant-sourced DOC from increasing vascular plant cover during the first summer following a fire (Davidson et al., 2019). Increases in DOC are correlated with increases in mercury contamination in northern pike (Pinel-Alloul et al., 2002). Higher levels of DOC in lakes on the Canadian Shield affected by fire, combined with higher averages of sulfate, often result in the stimulation of inorganic mercury in the lake (Garcia et al., 2004).

TOTAL PHOSPHORUS (TP)

Total Phosphorus Explained

When found in unpolluted surface waters, phosphates are derived from the decomposition of organic matter, as well as the leaching of minerals that contain phosphorus (Weiner, 2013). Phosphorus is also the limiting nutrient associated with the growth of aquatic vegetation, some of which may reach toxic levels. Phosphorus is greatly affected by wildfires and the severity of a fire. Lakes located within the Boreal Shield have an average total phosphorus (TP) concentration of 8.3 μg/L (Pinel-Alloul et al., 2002), with their trophic state ranging from oligotrophic to mesotrophic. Fires can result in changes to soils, lake trophic state, and the TP concentration within soils, in turn affecting post-fire exports of TP in runoff and streams. Increases in TP exports and concentrations following a fire can be extremely problematic for the surrounding environment.

Total Phosphorus as a Water Quality Parameter

Phosphorus is one of the main water quality parameters of concern following a watershed disturbance, such as a wildfire (Putz et al., 2003). Several studies indicate increases in TP in area lakes following a fire, for example a two-to seven-fold increase compared to undisturbed lakes (Pinel-Alloul et al., 2002) and an average TP three-fold higher than reference lakes (McEachern et al., 2002). A Canadian Shield lake can also experience increases in TP exports of over 90% following a wildfire (Wright, 1976). There is a natural phosphorus cycle in lakes that has a maximum phosphorus level during spring that is then reduced by approximately 50% in the following months (Carignan et al., 2000).

An increase in TP concentrations in Boreal Forest lakes can last upwards of nine years following a fire, with an example of increases remaining nearly four times normal levels during the fourth-year post-fire. In one burnt drainage area TP was six times higher than reference lakes during the first-year post-fire and twice as high as the reference lakes during the third-year postfire (Lamontagne et al., 2000). TP exports from another burned Boreal region watershed were nearly seven times higher than a reference watershed, remaining higher for three years following the fire (Putz et al., 2003).

Reasoning around Variations in Total Phosphorus

The high increase in TP in Canadian Shield lakes following fires is largely a result of an estimated 60% increase in runoff volumes, additional runoff in lakes accounts for two-thirds of the TP increase (Wright, 1976). Salvage cutting following fire appears to be another main factor in the increase of TP in surface waters, with hydrological changes within the catchments also contributing (Carignan et al., 2000). Phosphorus can be exported in organic and inorganic compounds, with increases also often related to increased rates in runoff following fire (Lamontagne et al., 2000). Depending on the removal of biomass during a fire phosphorus compounds remain in the area, which are then transported into streams resulting in impacts to stream productivity (Putz et al., 2003).

A ten-fold increase of TP causes major change to algal production (Wright, 1976). An increase in TP in burned lakes resulted in an 80% upsurge in biological activity, which is demonstrated by an increase in planktonic, algal biomass, zooplankton, and chlorophyll levels (St-Onge et al., 2000). The rapid seasonal variance in TP in burnt lakes is a result of its high bioavailability (Carignan et al., 2000). TP in burnt drainage areas is a strong indicator of the total primary production occurring within Boreal lakes, with algal and zooplankton biomass higher in these areas compared to reference areas (Lamontagne et al., 2000), and high levels of TP also resulting in increased phytoplankton abundance, as well as cyanobacteria (Putz et al., 2003).

TOTAL NITROGEN (TN)

Total Nitrogen Explained

Nitrogen is an essential nutrient and is also currently one of the greatest environmental concerns when elevated concentrations occur in waterways (Weiner, 2013). Excessive concentrations of nitrogen, often combined with phosphorus, are associated with algal blooms, eutrophication, and diminished dissolved oxygen, as well as linked to serious health concerns. Similar to phosphorus, increases in nitrogen and exports of nitrogen following a wildfire can result in many issues for waterbodies. Wildfires generate increased nitrogen through its mineralising in soils and vegetation (Pinel-Alloul et al., 2002).

Total Nitrogen as a Water Quality Parameter

For example, nitrogen exports increased by 7 to 15-fold following a fire in the Boreal Shield forest (Putz et al., 2003). Burnt Boreal Forest watersheds experienced two-to-four-fold higher nitrogen compared to reference watersheds (McEachern et al., 2000). From one source, total nitrogen (TN) has increased as much as 33% in Boreal Forest lakes following a fire (Lamontagne et al., 2000). From another, TN increased two-to seven-fold in fire impacted Boreal Forest lakes (Pinel-Alloul et al., 2002). Boreal Shield lakes have extended periods of high TN following a fire, with levels remaining nearly three-fold during the fourth year post-fire (Lamontagne et al., 2000). The first year post fire, streams in a Northwestern Ontario forest contained net nitrogen exports that continued to increase following stormflow events (Smith et al., 2011).

Reasoning around Variations in Total Nitrogen

Similar to phosphorus, nitrogen can be exported in mineral, organic and inorganic forms following a fire, in part explaining variation in the nitrogen levels in different regions (Lamontagne et al., 2000). Higher discharge and increased catchment-weighted discharge can also result in greater amounts of nitrogen entering waterways following a fire (McEachern et al., 2000). The high removal of biomass following a fire increases the amount of mobile nitrogen in the area, with the nitrogen moving into surrounding waterways and resulting in impacts to the productivity of the receiving waters (Putz et al., 2003). The higher amounts of nitrogen and phosphorus entering waterbodies following a fire can affect the abundance of phytoplankton and is also associated with cyanobacteria growth, which can dominate the aquatic ecosystem.

Riparian areas in the Boreal Forest are a transition between aquatic and terrestrial ecosystems. Riparian areas can also be heavily impacted by nitrogen with high-intensity wildfires, influencing the rate of concentrations entering water systems (Luke et al., 2007). Significant riparian disturbance can result in increased nitrogen entering into streams and rivers within the Boreal Forest. The impact of fires on the export of nitrogen is generally linked to bacterial behaviors in forest soils in response to fire amplifying mineralization rates and enhancing nitrification; mineralize nitrogen is extremely prone to leaching (Putz et al., 2003). Nitrogen will leach when the soil water content becomes greater than the maximum soil water holding capacity, typically as nitrate (Weiner, 2013). This form of leaching can become problematic when it removes too much nitrate content from the soil, resulting in over-acidic soil, which can also pose negative consequences for the surrounding waterways.

IRON (Fe)

Iron Explained

Iron is a heavy metal that occurs naturally throughout the environment including in soil, water, and rocks, by ways of erosion and weathering of rocks and minerals. Iron can also enter the natural environment as a result of mining activities, acidic mine water drainage, and from iron-related industries. Iron is an essential nutrient for plants and animals and is present in organic matter in soils. Iron is naturally released into the environment through the weathering of ores that contain iron sulfide as well as other iron bearing minerals in metamorphic, igneous, and sedimentary rocks (Weiner, 2013). Within water, iron commonly occurs with manganese but is typically more abundant. Canadian drinking water guidelines for iron pertain to an aesthetic (or taste) objective of equal to or less than 0.3 mg/L (Government of Canada, 2017).

Iron as a Water Quality Parameter

Instream concentrations of iron are elevated following a fire (Bladon et al., 2014). Iron increased by factors of three during post-fire monitoring of a burnt reservoir (Abraham et al., 2017). Metal concentrations sampled following a fire indicated an increase in 2 to 2500 times for concentrations of several metals including iron, with mean iron levels remaining elevated five years post-fire (Bladon et al., 2014). Water quality samples were collected from upstream and downstream of a burned area during storm events, with iron concentrations exceeding drinking water standards at these times (Murphy et al., 2020). Concentrations of dissolved iron also exceeds secondary drinking water standards in areas where severe forest fires have occurred (Pacheco et al., 2021). Iron drinking-water standards were exceeded downstream following the first significant post-fire precipitation event as well as during post-fire storm events (Murphy et al., 2020). Heavy rainstorms contributed to close to 3000 tons of sediment and metals including iron being dumped into the watershed following a high intensity wildfire (Struzik, 2018). In one case following a fire, fire-generated debris flowed throughout a riverway resulting in concentration over 2000 times the guideline value (Abraham et al., 2017). Water quality following a large intensity fire included iron concentrations recorded at elevated levels of 255 times guideline values and compared unfavourably to 20 years of pre-fire levels.

Reasoning around Variations in Iron Concentration

Wildfires can release heavy metals, such as iron, that have accumulated for years or decades from high pulses from the atmosphere in both terrestrial and aquatic ecosystems (Bladon et al., 2014). Because fire is able to discharge and remobilize metals from plants and soil, the result is high levels of iron and other metals being transported to downstream waterbodies through runoff (Abraham et al., 2017). Downstream water contamination with iron can be a result of mineralization of organic matter generated by a wildfire. Downstream iron increases are also a result of post-fire soil erosion being increased by high-intensity precipitation events.

Fires that have impacted watersheds exploited by the mineral industry or those in close proximity to mining procedures, even those that have been subsequently revegetated, may cause higher risks to downstream water supplies (Murphy et al., 2020). The combination of the two disturbances can enhance the possibility of increased loads of sediment and metals in streams in the area. The increased possibility of mobilized metals in streams is because of the exposure of mine tailings.

MERCURY (Hg)

Mercury Explained

Mercury (Hg) is significant among environmental pollutants by virtue of its volatility and the ease by which inorganic mercury can be converted to organic forms (Weiner, 2013). Because mercury is highly volatile and toxic it can pose risks to the environment, wildlife and human health. The World Health Organization (WHO) guidelines for drinking water quality indicate that safe consumption of mercury in drinking water means levels below 0.006 mg/L (Smith et al., 2011), with Canadian drinking water quality guidelines indicating safe consumption of mercury is at mean levels below 0.001 mg/L (Government of Canada, 2009). Once mercury enters into a terrestrial system, it can accumulate in forest soils and be slowly transported to surface and deep waters, where it will accumulate in biota and sediment (Lintner et al., 2021).

Mercury as a volatile substance, is extremely dangerous to any species, even at low levels, with nearly all mercury compounds being toxic. Mercury is a continual persistent substance that can bioaccumulate in living organisms and can work its way up a food chain, causing toxic impacts to all organisms that consume it. Throughout the environment, especially in waterbodies and wetlands, mercury can be converted into a highly toxic organic compound known as methylmercury (MeHg) (Government of Canada, 2013).

Reasoning around Variations in Mercury as a Water Quality Parameter

Canadian Shield lakes have experienced increases in mercury and MeHg, of eight and ten-fold, respectively, following a fire (Garcia et al., 2005). Metal concentrations, including mercury, increased two to 2500 times post-fire, with mercury levels exceeding guidelines for two-years post-fire (Bladon et al., 2014). Mercury in forest ecosystems can accumulate through atmospheric deposition from natural and anthropogenic sources, and mercury can then be re-volatilized during wildfires (Smith et al., 2011). Burnt soils and ashes can result in the re-mobilization of mercury, with aqueous concentrations increasing during post-fire rain events (Pacheco et al., 2021). Watershed disturbances can modify mercury export rates to waterbodies and affect in-lake reactions, with fires generating nutrient pulses, affecting the formation and availability of mercury and MeHg (Garcia et al., 2005). Significant inputs of mercury concentrations in watersheds are a result of high-runoff periods (Moingt et al., 2013).

Mercury has the potential to biomagnify and bioaccumulate, both having the potential to result in serious health concerns for consumers of fish. Larger fish consume and bioaccumulate more mercury. A fire released such high levels of mercury that government officials had to issue a health warning for fish consumption by humans (Struzik, 2018). The dynamics and concentrations of mercury in Boreal Forest lakes have been an ongoing and growing subject of concern for several years due to human exposure, largely through fish consumption.

Mercury and Fish

Wildfires can result in elevated mercury and methyl mercury concentrations in sediment as well as the fish within the disturbance area, with some mercury levels exceeding the guideline limits for human consumption in fish. High mercury concentrations have been reported in predatory fish species Boreal lakes in North America (Garcia et al., 2005). Mercury levels exceeded the recommended limit for human consumption in northern pike, walleye, and burbot in burn impacted lakes.

In lakes in the Canadian Shield, fires can affect the abundance of fish, particularly yellow perch and white sucker, because fine sediment can reach the shorelines affecting the survival and habitats of macroinvertebrates, prey for these species (St-Onge et al., 2000). The removal of vegetation by fires can also affect spawning habitat quality. Piscivorous species inhabiting higher trophic levels display the highest concentrations of mercury with changes to mercury cycling being linked to watershed disturbances (Garcia et al., 2005).

The Government of Ontario provides recommendations for consumption of sport fish related to mercury concentrations by means of the Ontario's Ministry of Environment's published *Provincial Fish Consumption Advisories* guide. Consumed quantities of sport fish are restricted beginning at equivalents of 0.26 ppm for women of childbearing age and children under the age of 15, with complete restrictions for levels above 0.52 ppm; recommendations for the general populations begin at equivalents of 0.61 ppm, with complete restrictions for levels above 1.84 ppm (Government of Ontario, 2013).

High levels of mercury in the fish in Ontario's Boreal lakes is of great concern, as numerous Indigenous communities rely on fish as a food source. Mercury levels began being monitored in fish during the 1970s. This rather late start is of great concern for people living in Indigenous communities due to the serious health concerns related to high mercury consumption in the past. Fish are an important food source and provide a means of traditional cultural practices for Indigenous communities.

AMMONIA (NH_3)

Ammonia is a colourless gas that is naturally present in most surface waters and is a form of nitrogen that can cause direct toxic effects on aquatic lifeforms (Weiner, 2013). Canadian drinking water guidelines suggest limiting ammonia entering a water distribution system to less than 0.1 mg/L in order prevent nitrification (Government of Canada, 2020). Ammonia is generally produced for commercial and industrial uses, with natural sources of discharge including the decomposition of organic matter waste, forest fires, and nitrogen fixation (Bergeron, 2013). Ammonia can enter into aquatic environments via direct means, such as effluent discharges from commercial or industrial applications, as well as indirect means such as runoff, air depositions, and fire impacts. Ammonia concentrations as low as 0.03 mg/L can potentially be toxic to aquatic organisms in the short term, with concentrations greater than 0.001so mg/L being potentially toxic over long term (Pike et al., 2005).

Dissolved ammonia reacts with water as a base in natural waters, raising the pH level through the generation of oxygen and hydrogen isotopes (OH^-) (Weiner, 2013). High levels of ammonia in water and aquatic environments can result in death of aquatic organisms because the high levels of ammonia make it difficult for organisms to adequately expel the toxicant, ultimately leading to buildup of the toxin throughout internal tissues and the bloodstream (Bergeron, 2013). Accumulated ammonia can also result in reduced growth rates, poor food conversion, and reduced disease resistance for aquatic species (Weiner, 2013). Other environmental factors, such as pH, can affect ammonia's toxicity to aquatic organisms. The pH of unpolluted river water is generally between 6 and 9, with pH of unpolluted groundwater generally between 5.5 and 8.5. The conversion of ammonium to ammonia is pH dependent. Both can exist in water, but ammonia is only stable when pH is greater than 9, with concentrations of ammonia decreasing tenfold with each decrease is pH unit (Pike et al., 2005). Under low pH conditions, (acidic) metals tend to dissolve, making ammonia less toxic to fish, whereas under high pH conditions (basic) metals tend to precipitate as hydroxides and oxides, and ammonia becomes more toxic to fish.

ZINC (Zn)

Zinc is a common contaminant in surface waters and groundwater, occurring in both suspended and dissolved forms (Weiner, 2013). In unpolluted surface waters, zinc concentrations typically range between 5 and 50 ug/L, with streams draining areas of active mining often exceeding 100ug/L. The World Health Organization suggest a human consumption legal limit of 5 mg Zn/L. One of the most mobile heavy metals found in surface waters and groundwater, zinc forms soluble compounds at both neutral and acidic pH values. Weiner (2013) further explains that the solubility of zinc heavily depends on temperature and pH of the water. When pH is neutral zinc is water insoluble with solubility increasing with increasing acidity. Forest catchment studies also reveal that zinc mobility is dependent on pH (Abraham et al., 2017). At higher pH values zinc can form carbonate and hydroxide complexes, which control zinc solubility, with dissolved zinc being readily absorbed in mineral clays and humic colloids (Weiner, 2013). The mobilization of metals, including zinc, can be heavy influenced by the occurrence of wildfires and fire-induced pH changes to burned soils (Gill, 2004).

Zinc concentrations are positively correlated with mass loss and vegetation loss following fires (Kondratova and Bryanin, 2021). Post-fire plant growth is negatively correlated with postfire total metal concentrations and fluxes (Rust et al., 2019). Total metal loading rate is considerably correlated with soil field capacity, with slower vegetation recovery during the first post-fire year correlated with increased loading rates for zinc. Zinc concentrations are influenced by the change in vegetation cover already the first year after a fire, with concentration increases two-fold 3.5 years post-fire.

Zinc is extremely mobile and easily absorbed by plants, with plants being an intermediate reservoir of metals absorbed from soils, water, and air (Abraham et al., 2017). Precipitation events wash the metals from plants into soils and waterways, thus enhancing zinc mobility as this metal is extremely mobile and considerably more mobile in soils of low pH. In burned streams, soil organic matter impacted the response of zinc, with burned catchments having higher zinc concentrations (Rust et al., 2019). Zinc concentration in wetland plant tissues and soils are significantly mobilized by wildfires (Abraham et al., 2017). Elevated zinc concentrations in surface waters may be a result of the remobilization of mine waste eroded from hillslopes and stream banks, deposited in stream channels and floodplains during storms. In one study, elevated concentrations of zinc persisted for months to years, with post-fire samples in stream tributaries containing higher concentration of zinc compared to downstream (Murphy et al., 2020).

Post-fire concentrations of zinc were reported as 21-74 percent above background levels within a few months post fire (Gill, 2004). Wildfire severity has been positively correlated with post-fire increases in metals, including zinc, in streams (Rust et al., 2019). Zinc concentrations are nearly four-fold in burned areas, with concentrations increasing two-fold two years post-fire (Kondratova & Bryanin, 2021). A Boreal forest study revealed heavy metals have particular dynamics following a wildfire, and zinc releases slowly with post-fire concentration levels returning to normal eight to eleven years following the fire (Kondratova & Bryanin, 2021). Murphy et al. (2020) further supported this finding as elevated zinc concentrations in streams draining the burned areas continued for a five year period post-fire. High concentration of zinc in waterbodies can be fatal to fish as well as result in impairments to other aquatic biota in Boreal forest streams (Rust et al., 2019).

Rainfall runoff and storm events throughout burnt forests have the capacity to produce flows that carry large sediment loads enriched with zinc into surface water resources (Abraham et al., 2017). Zinc concentrations were reported to be 1.2 times higher in samples of stormwater runoff immediately following a wildfire in a mixed-conifer forest (Smith et al., 2011). Post-fire runoff events water samples revealed zinc concentrations 1.2 times higher than before the fire (Abraham et al., 2017). An intense post-fire storm event resulted in elevated zinc concentrations, reported at 50 times higher than pre-fire concentrations (Abraham et al., 2017). Contaminant loading post-fire involved zinc concentrations between 112 and 736 times higher in the watersheds of burned catchments (Abraham et al., 2017).

METHODS

STUDY AREA

The study area is located on the Canadian Shield in the Boreal forest region of Northwestern Ontario, where an intensive wildfire occurred during the summer of 2011 burning 141 000 hectares of forestland in close proximity to a mine site. As the study area is in the Boreal region, forests are dominated by coniferous species. The main coniferous species are *Picea mariana* and *P. glauca, Pinus banksiana, Abies balsamea, Larix laricina*, and *Thuja occidentalis*, with the predominant deciduous species *Betula papyrifera* and *Populus tremuloides*. Some of the most significant physical features of the Boreal region include thousands of small lakes, thin layers of soil, and bedrock composed of ancient granite (Mackie, 2001). The topography consists of rolling uplands combined with numerous forms of wetlands. The lakes are largely the result of glacial erosion during the last ice age.

The data was collected pre and post fire from five regional water quality stations, six local water quality stations and six lake water quality stations, with all stations within a 20 km^2 area of a mine site. This study compared water quality characteristics over a ten-year timeframe, 2006 through 2016, including five years pre-fire and five years post-fire data from various water quality stations within the study area. Water quality stations were selected to include data from upstream and downstream of the mine site in order to examine possible variations in water quality characteristics following the fire disturbance in combination with effects of the mine.

WATER QUALITY STATION LOCATIONS

The water quality stations are divided into three categories as follows, Regional Water Quality Stations, Local Water Quality Stations and Zeemel Lake Water Quality Stations. The fire burnt over 141 000 hectares of forestland, with water quality stations located both within and out of the fire boundary (Figure 1).

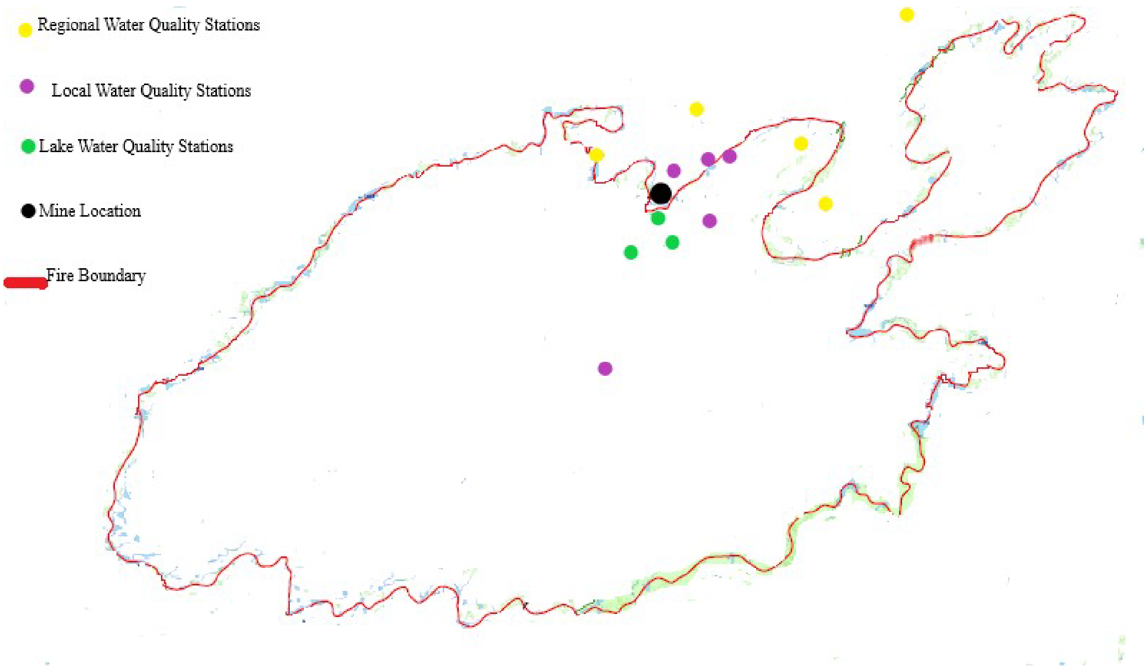


Figure 1. Map of the study region showing the fire boundary and water quality stations

SAMPLING AND DATA ANALYSIS

The water was sampled for water quality tests at the stations numerous times each year during the ice-free season, typically during the months of March through November. Collection dates varied for the different water quality stations. Samples were filtered, stored, and analyzed within standard methods. Measured properties for this study include dissolved organic carbon (DOC), pH, total phosphorus (TP), total Kjeldahl nitrogen (TKN), mercury (Hg), iron (Fe), ammonia (NH_3), and zinc (Zn).

All properties were measured following ALS Certificate of Analysis Testing Methods (2021). DOC was measured by combustion. Filtered samples were acidified and purged to remove inorganic carbon, then injected into a heat reaction chamber where organic carbon is oxidized to CO2, which was transported in the carrier gas stream and measured via a nondispersive infrared gas analyzer. pH was measured using procedures adapted from the APHA Method 4500-H, determined in the laboratory using a pH electrode. TP was measured using a discrete analyzer with colorimetric detection. Total Kjeldahl nitrogen and ammonia were determined using block digestion followed by flow-injection analysis with fluorescence detection. Mercury concentration was determined by a cold-oxidation analysis. Iron and zinc were determined through digestion with nitric and hydrochloric acids.

Graphs of the data were created in Microsoft Excel, separated into upstream and downstream stations relative to the mine site and plotted against flow for each individual water quality station (See Appendices). Where there were sufficient replicates on a watershed the data were averaged. Averaging was done for stations with the same or very similar collection dates for flow and water quality. Upstream stations that could be averaged were MUS-01 and MUS-09, BRG and MUS-04, and ZL1B, ZL1T and ZL2T. Downstream stations were MUS-02, MUS-08 and MUS-10, MUS-18, MUS-22, MUS-24, and MUS-31.

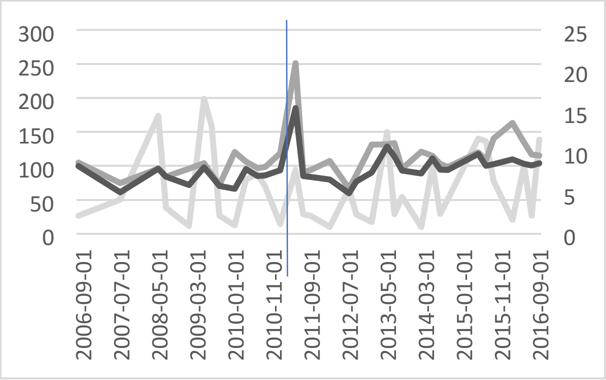
RESULTS

CONDITIONS UPSTREAM OF THE MINE SITE

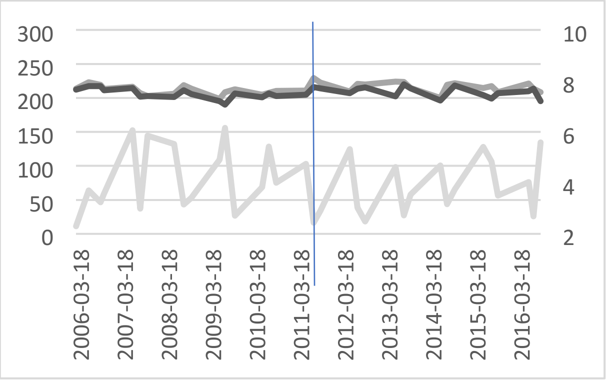
Upstream of the mine site, there were two pre-fire peak flow events that were higher than any post-fire flow event (Figure 2). Flows, higher in spring and lower later in the year, were otherwise similar in pattern throughout the monitoring period. Nutrient and metal concentrations were positively correlated with flow, higher following increased flow events. Post-fire concentrations of DOC were somewhat higher than pre-fire concentrations. The highest increase in DOC occurred at local station BRG upstream of the mine site during the fourth year post-fire; the increase persisted through the autumn months, and the same occurred at station ZL2T during the summer months of years two and five post-fire (Appendix I). There was one sharp peak in DOC concentration immediately following the fire that was evident across all upstream stations (Figure 2). Meanwhile, pH was relatively consistent throughout the monitoring period. A decrease in pH occurred in the third year post-fire at stations BRG and MUS04 (Appendix I).

Pre-fire concentrations of all nutrients, TP, TKN and NH3, were higher than post-fire concentrations (Figure 2). The highest increase in post-fire TP concentrations occurred during the third year throughout the summer months, as well as during the summer months of the fourth and fifth post-fire years. TKN concentrations increased upstream during the first, second and fourth post-fire years, especially during the summer months, with the highest increase occurring during the fourth post-fire year. The highest post-fire increases in NH3 occurred during the third year following the fire, with increases occurring during the summer and autumn months. Like the nutrients, pre-fire concentrations of all metals, Hg, Fe and Zn, were higher than post-fire concentrations. Hg concentrations increased during the second and third post-fire years, to levels like before the fire. Meanwhile, sharp increases and decreases of Zn concentrations occurred during years four and five post-fire, respectively.

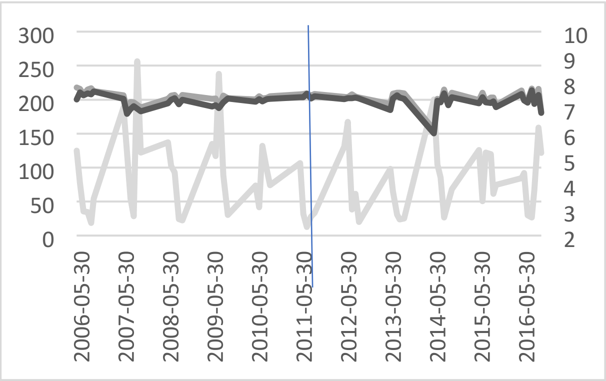
DOC- stations ZL1B, ZL1T, ZL2T



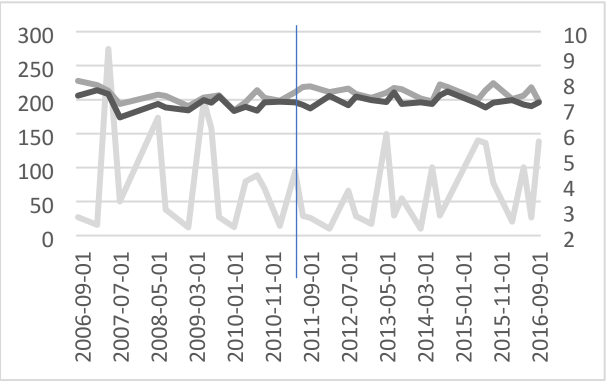
pH- stations MUS01, MUS09



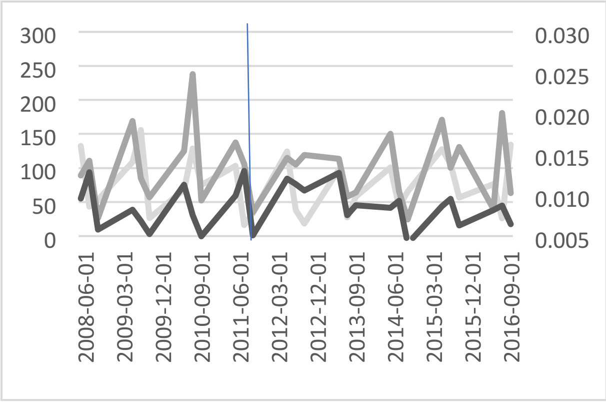
pH- stations BRG, MUS04



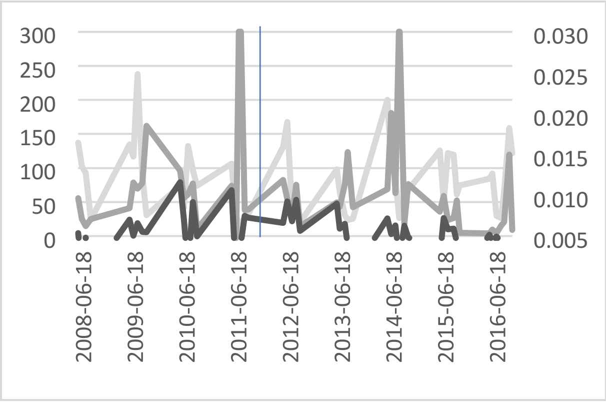
pH- stations ZL1B, ZL1T, ZL2T



TP- stations MUS01, MUS09



TP- stations BRG, MUS04



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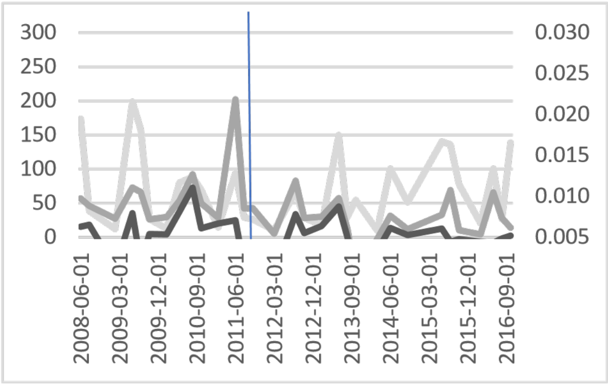
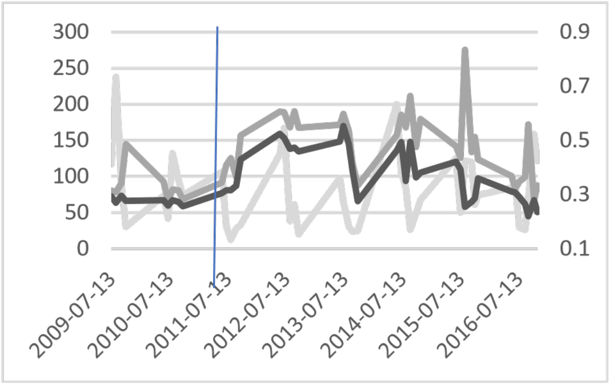
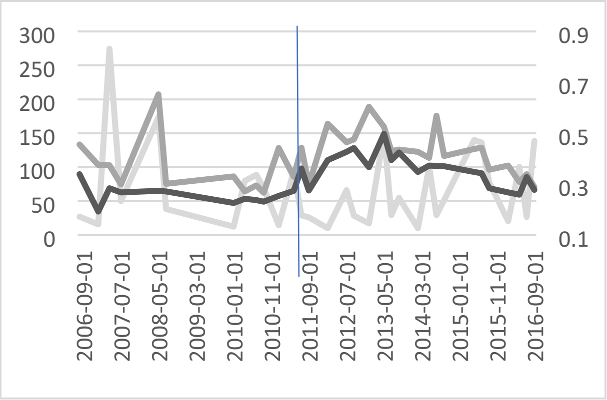
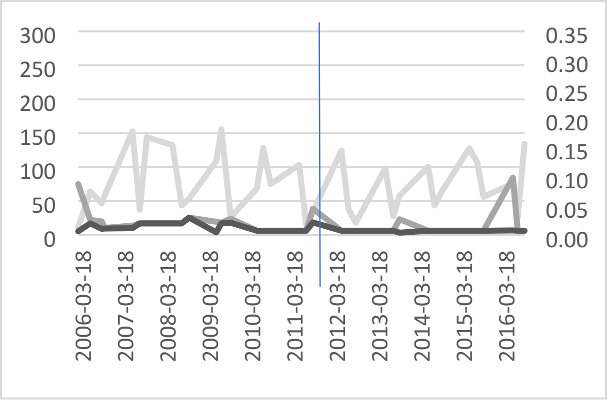
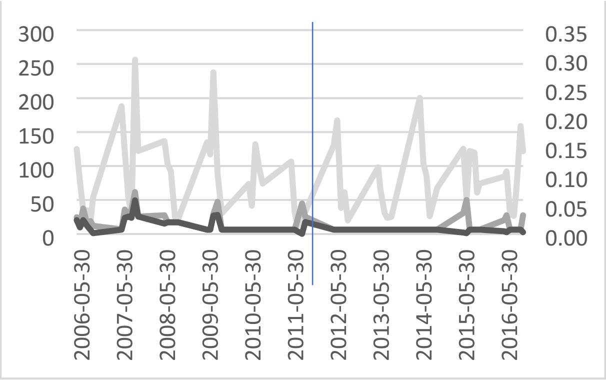

TP-stations ZL1B, ZL1T, ZL2T


TKN- stations BRG, MUS04


TKN- stations ZL1B, ZL1T, ZL2T


NH3- stations MUS01, MUS09


NH3- stations BRG, MUS04

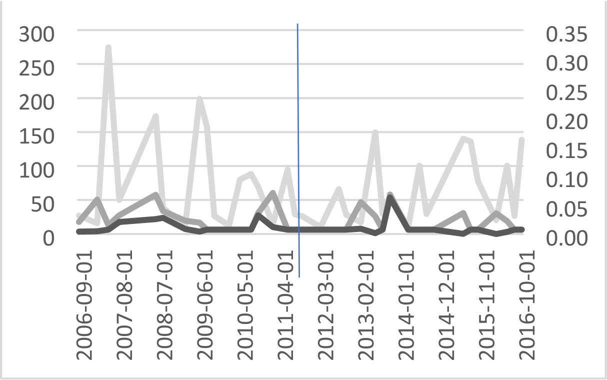
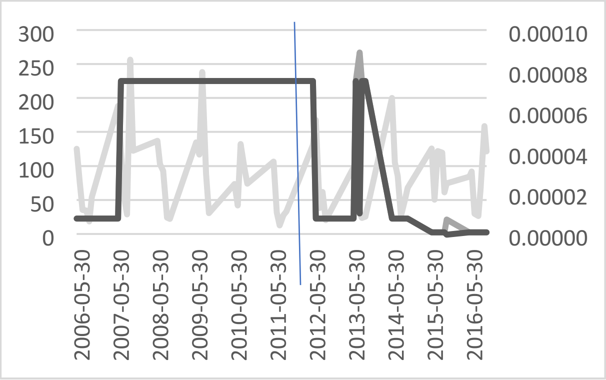
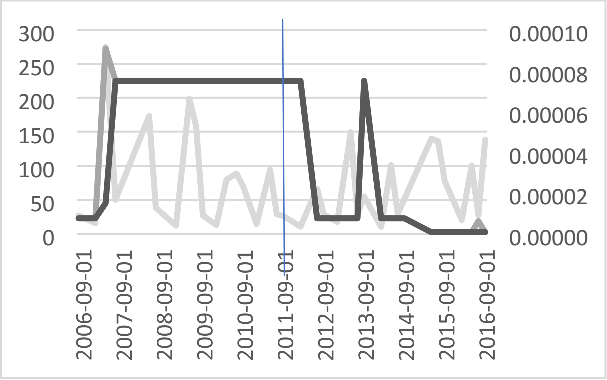

NH3- stations ZL1B, ZL1T, ZL2T

Figure 2 is continued on the next page.

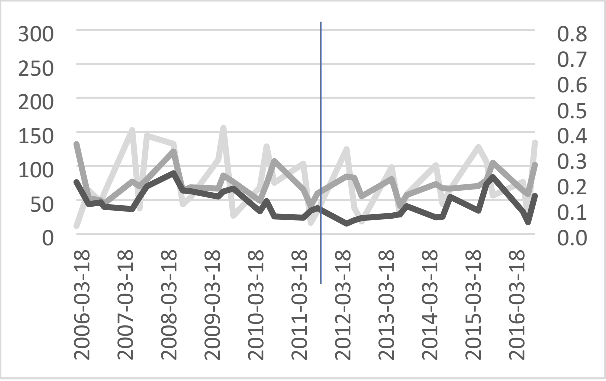
Hg- stations BRG, MUS04



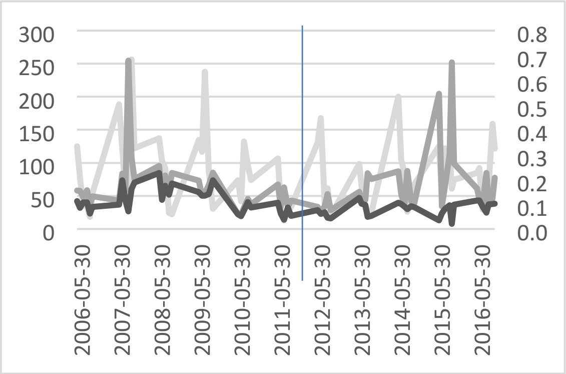
Hg- stations ZL1B, ZL1T, ZL2T



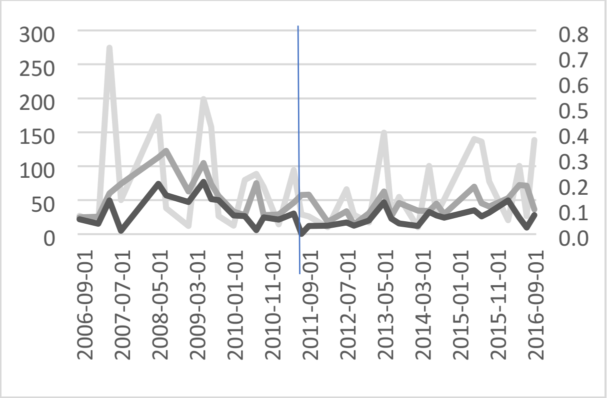
Fe- stations MUS01, MUS09



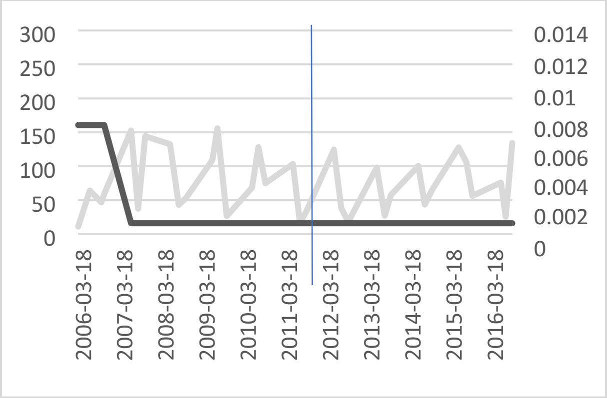
Fe- stations BRG, MUS04



Fe-stations ZL1B, ZL1T, ZL2T



Zn- stations MUS01, MUS09



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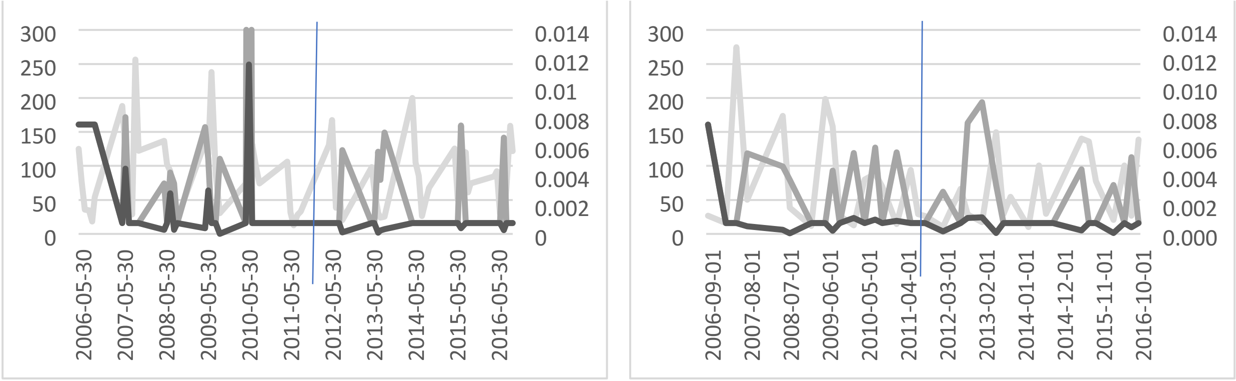

Zn- stations BRG, MUS04

Zn- stations ZL1B, ZL1T, ZL2T

Figure 2. Upstream flow to the Northern Ontario mine, light grey lines (left axis), Dissolved Organic Carbon (DOC), pH, Total Phosphorus (TP), Total Kjeldahl Nitrogen (TKN), magnesium (Mg), iron (Fe), ammonia (NH3), and zinc (Zn) concentrations, darker grey lines (right axis). Fire occurrence date is displayed as a vertical line.

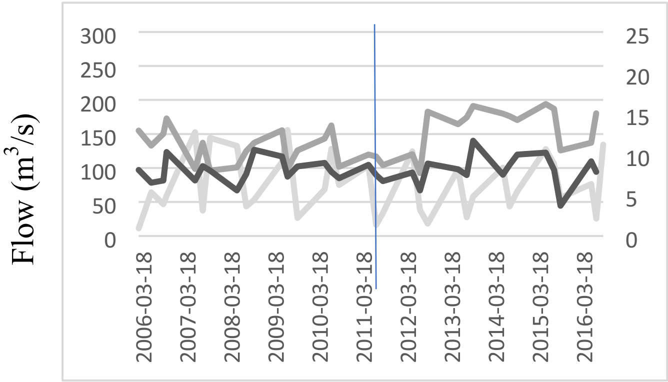
CONDITIONS DOWNSTREAM OF THE MINE SITE

Downstream of the mine site, stream flows were similar before and after the fire, but two peak flow events occurred before the fire, a third immediately following the fire, and a fourth in the third year after the fire (Figure 3). As for the upstream conditions, nutrient and metal concentrations were positively correlated with flow, higher following increased flow events. Both pre- and post-fire concentrations of DOC were higher downstream than upstream, with higher concentrations occurring during the first three post-fire years. The highest increase of DOC occurred at station MUS10 over the second to fifth post-fire years, with the highest concentrations measured in June and August of the third and fourth post-fire years (Appendix II). Downstream pH was relatively consistent throughout pre- and post-fire years, but post-fire pH was higher downstream compared to upstream (Figures, 2, 3). Pre-fire downstream concentrations of TP were higher than after the fire. Post-fire concentrations of TP were higher downstream compared to upstream. The highest increase of TP concentrations occurred one year post-fire during the summer months for all downstream stations, with the exception of station

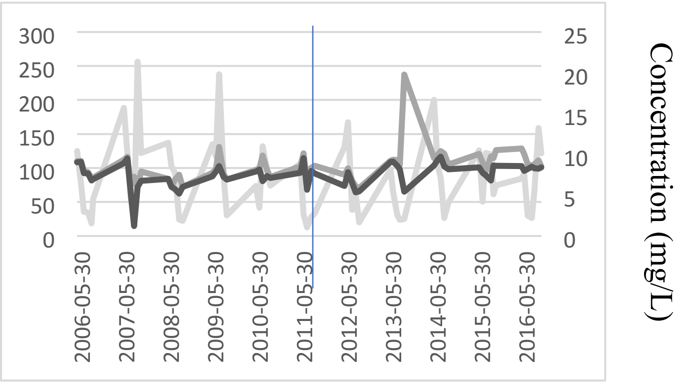
MUS31, and the highest concentrations occurred in September through October (Appendix II). Opposite to TP, post-fire concentrations of TKN were slightly higher upstream compared to downstream, but like for TP, downstream TKN was higher post-fire than pre-fire (Figures, 2, 3). Like TP, downstream post-fire NH3 concentrations were higher compared to upstream concentrations, and higher compared to pre-fire concentrations. TKN and NH3 concentrations increased during the summer months of the first through fifth post-fire years, with highest increases during the second and fourth years.

Downstream pre-fire concentrations of Hg, Fe and Zn were higher compared to post-fire concentrations (Figure 3). Downstream post-fire concentrations of Mg and Fe were higher than upstream concentrations for the first three years following the fire (Figures 2, 3). Post-fire downstream concentrations of Zn were higher than upstream concentrations during the fourth and fifth post-fire years. Elevated Hg concentrations occurred downstream of the mine site during the second and third post-fire years, and elevated Zn concentrations occurred in the first, second and fourth post-fire years. Downstream heavy metal concentrations were positively correlated with flows, with high increases following peak flow events.

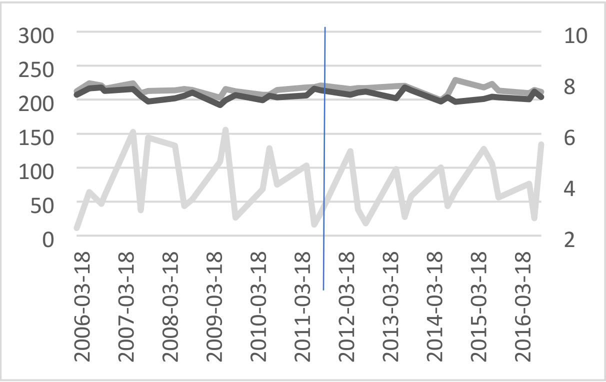
DOC- stations MUS08, MUS10



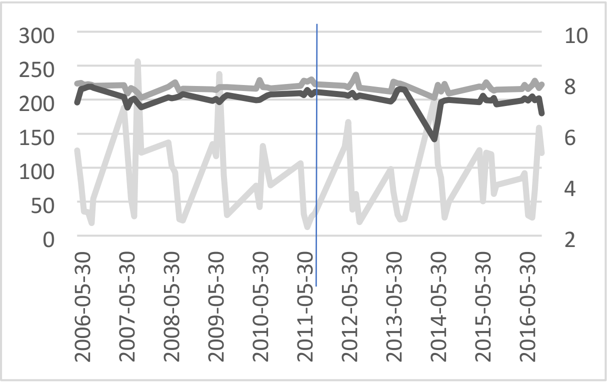
DOC-stations MUS18, MUS22, MUS24



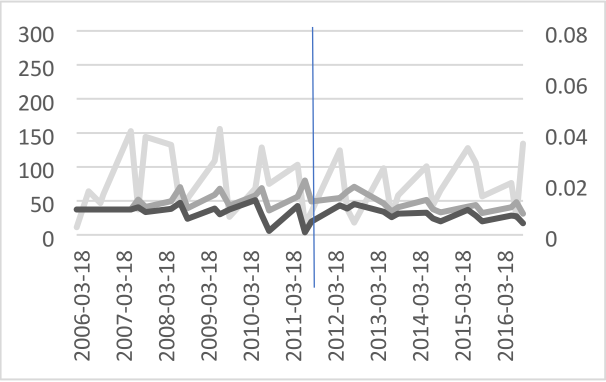
pH- stations MUS02, MUS 08, MUS10



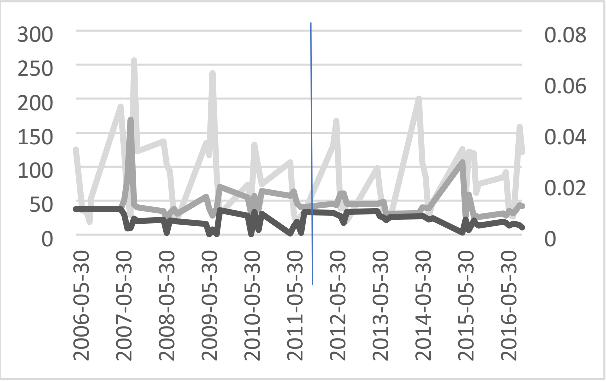
pH- stations MUS18, MUS22, MUS24, MUS31



TP- stations MUS02, MUS08, MUS10



TP-stations MUS18, MUS22, MUS24, MUS31



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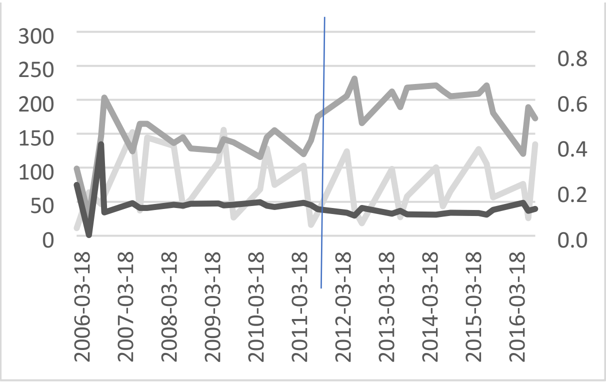
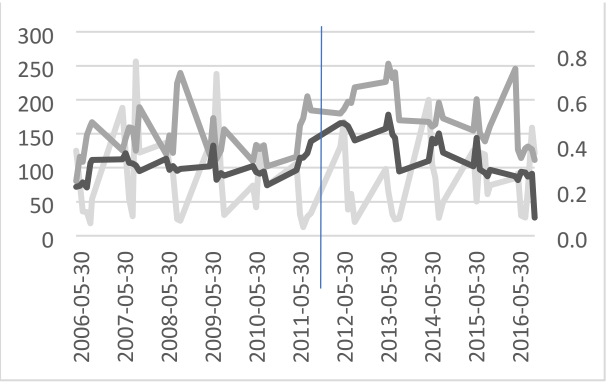
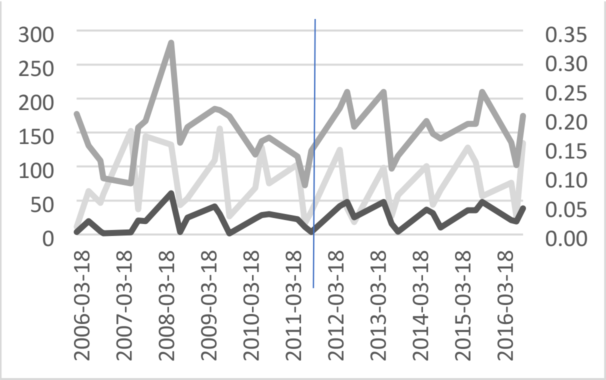
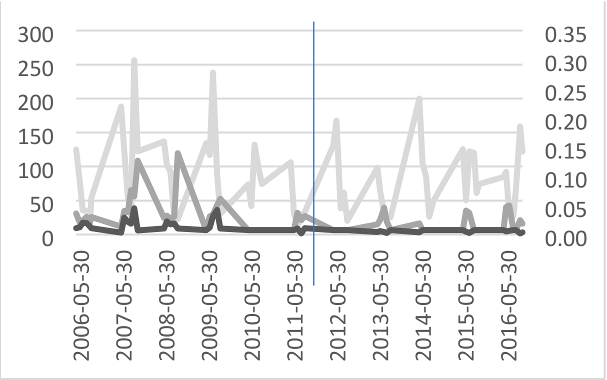
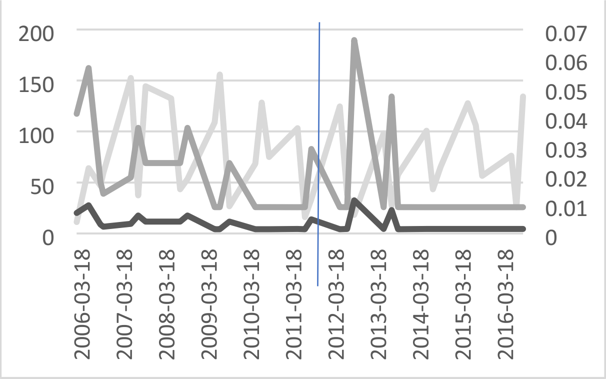

TKN-stations MUS08, MUS10


TKN-stations MUS18, MUS22, MUS22, MUS31


NH3- stations MUS02, MUS08, MUS10


NH3- stations MUS18, MUS22, MUS24, MUS31


Hg- stations MUS08, MUS10

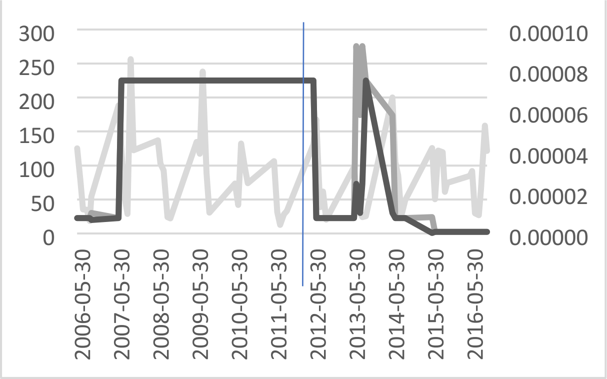
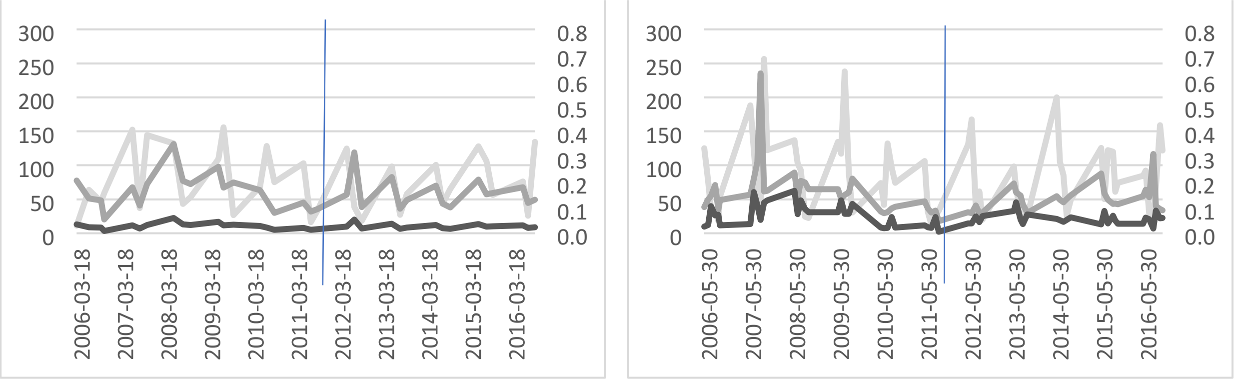

Hg- stations MUS18, MUS22, MUS24, MUS31

Figure 3 is continued on the next page.

Fe- stations MUS08, MUS10 Fe- stations MUS18, MUS22, MUS24, MUS31



Zn- stations MUS02, MUS08, MUS10 Zn-stations MUS18, MUS22, MUS24, MUS31

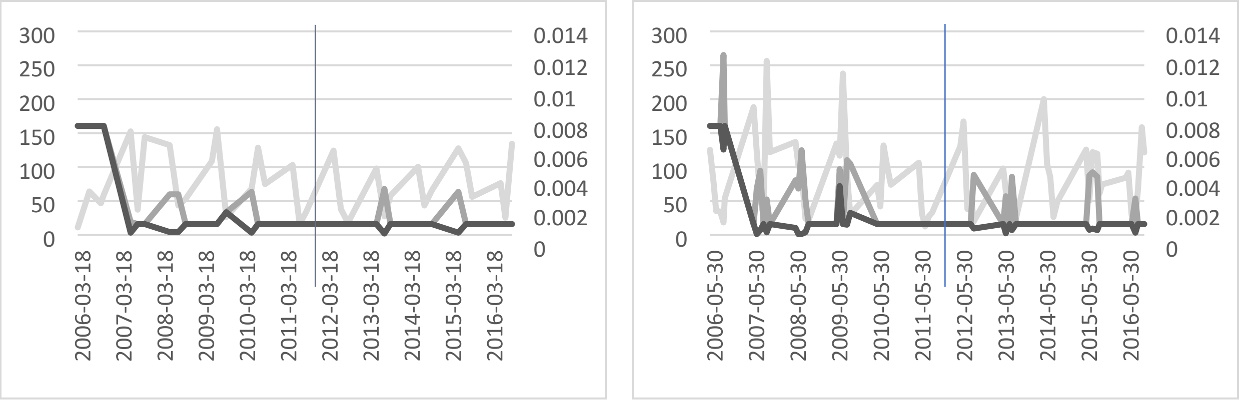


Figure 3. Downstream flow from the Northern Ontario mine, light grey lines (left axis), Dissolved Organic Carbon (DOC), pH, Total Phosphorus (TP), Total Kjeldahl Nitrogen (TKN), magnesium (Mg), iron (Fe), ammonia (NH3), and zinc (Zn) concentrations, darker grey lines (right axis). Fire occurrence date is displayed as a vertical line.

DISCUSSION

The forest fire appears responsible for increases in flow and decreases in water quality both upstream and downstream of the mine site. DOC and NH3 concentrations generally increased with increased flow, especially downstream of the mine site. However, TKN and TP did not increase downstream after the fire. Heavy metal concentrations always increased with an increased flow, but pre-fire concentrations were higher than after the fire. The highest levels of post-fire DOC concentrations occurred during the summer months, May through August, with a positive correlation having occurred with flow. These findings match literature that suggests DOC concentrations increase post-fire, particularly during the summer months (Davidson et al., 2019). Post-fire downstream mean DOC concentrations measured between 12.5 and 8.9 mg/L, with upstream mean concentrations measured between 9.4 and 8.6 mg/L, revealing a potential influence of flow through the mine site. A sequence of components may be responsible for this downstream increase in DOC. One is increased post-fire water tables that are caused by reduced evapotranspiration, especially where runoff bypasses DOC absorbing soils and enters pooled areas of cleared forest around the mine, with increased water tables also contributing to increased flow paths and enhanced transport of DOC from terrestrial to aquatic systems (Putz et al., 2003). Post-fire DOC data supports previous published literature.

The forest fire resulted in increased TKN and NH3 concentrations and had little to no implications on TP concentrations. The findings suggest higher TKN export rates compared with TP export rates following the fire. Downstream post-fire concentrations of NH3 were higher compared with upstream concentrations, with increases having occurred during the summer months of all post-fire years. However, TKN post-fire concentrations increased more upstream. Increases in nitrogen concentrations may be explained in part by the forest fire impact on mineralising the vegetation and soil surrounding lake basins (Pinel-Alloul et al., 2002). Upstream and downstream pre-fire heavy metal concentrations were higher compared to post-fire concentrations, alleviating concerns around increased mercury concentrations in downstream lakes.

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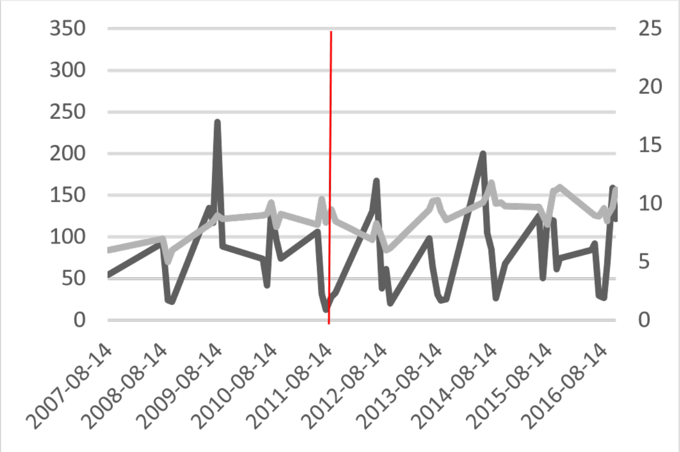
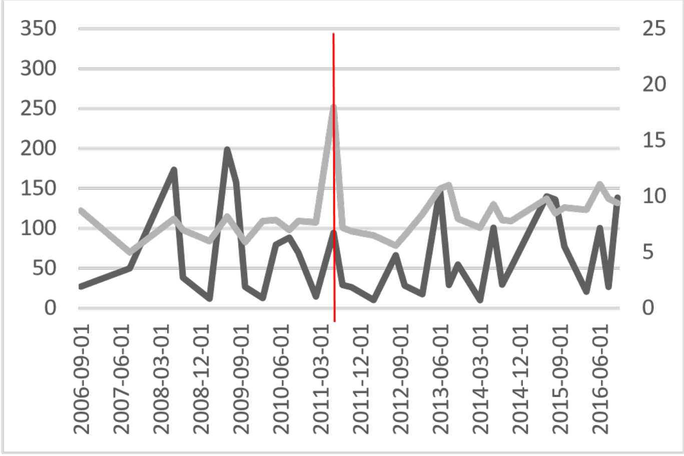
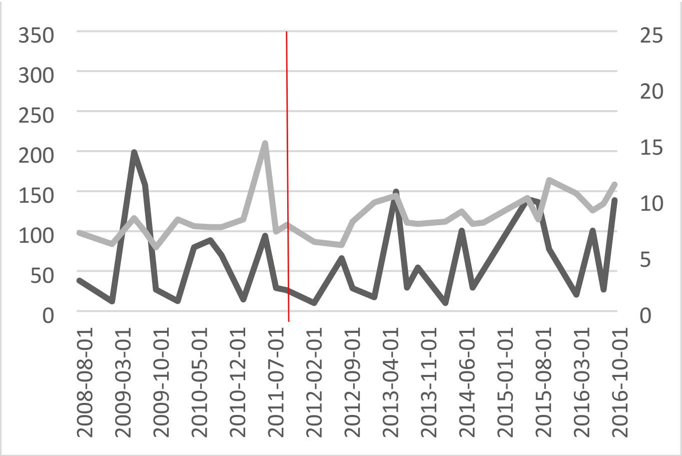
APPENDIX I

Upstream Graphs, i.e., upstream of the mine site.

1. Dissolved organic carbon, dark grey lines, right axis, and stream flow, light grey line, left axis. Vertical line displays the date of fire occurrence.



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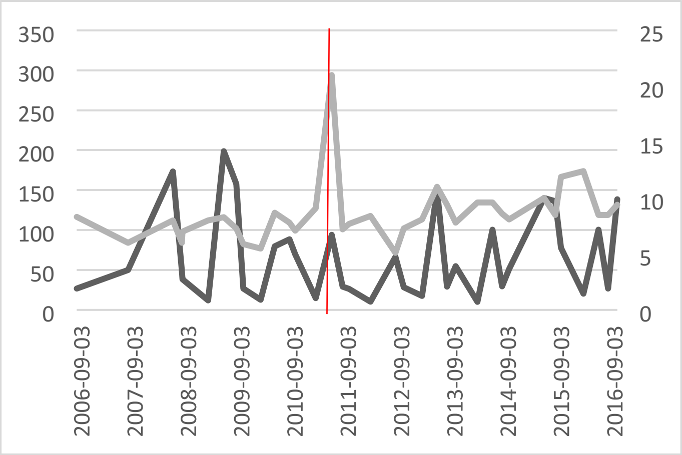
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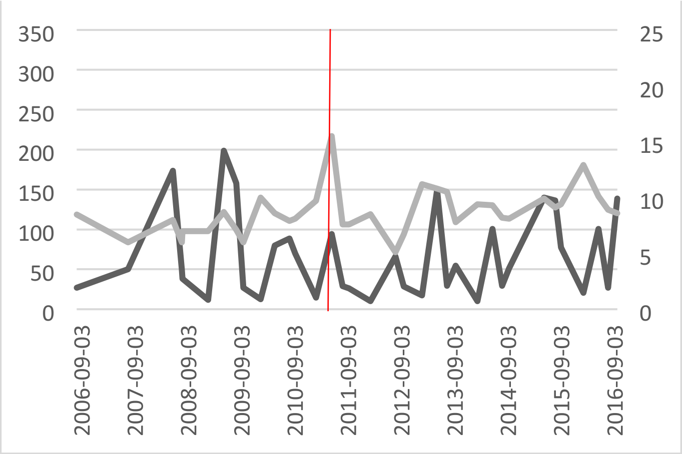
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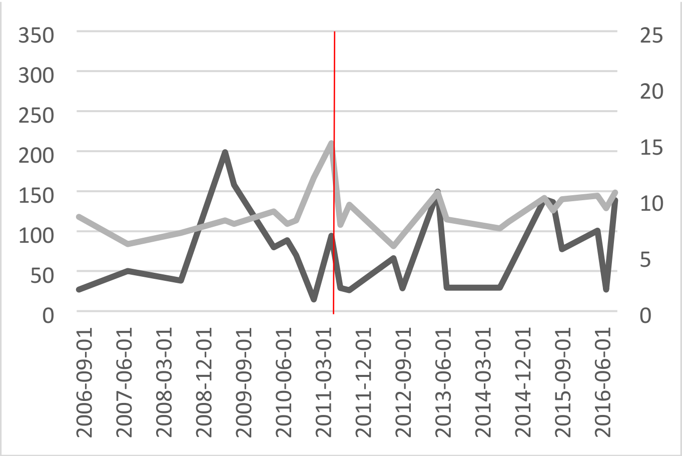
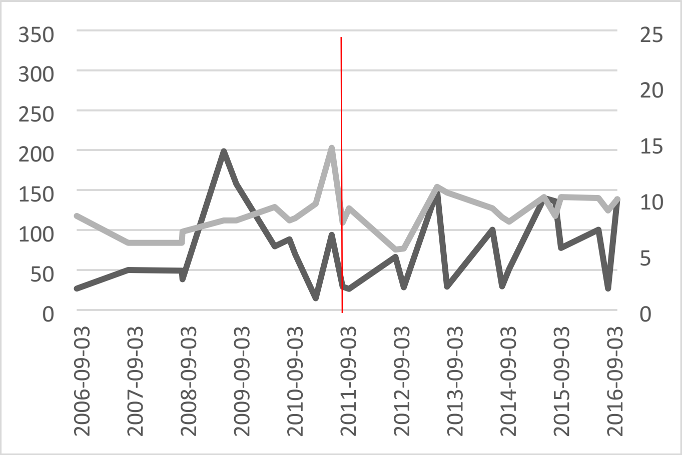
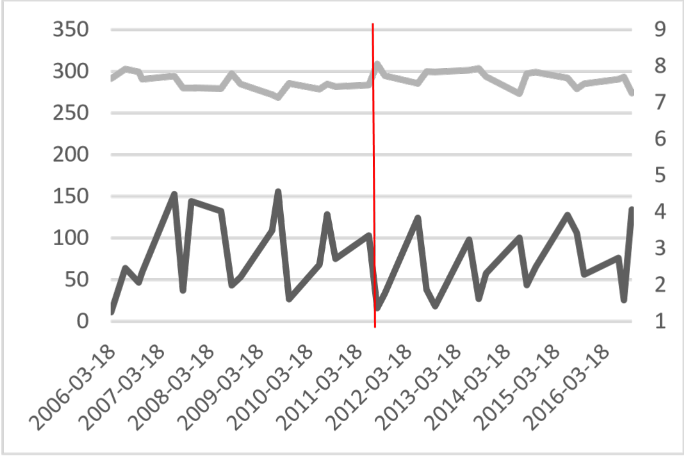
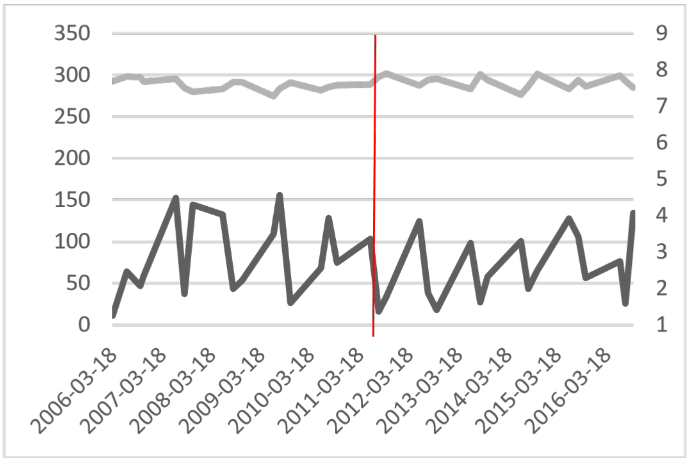




2. pH concentration, dark grey lines, right axis, and stream flow, light grey line, left axis. Vertical line displays the date of fire occurrence.

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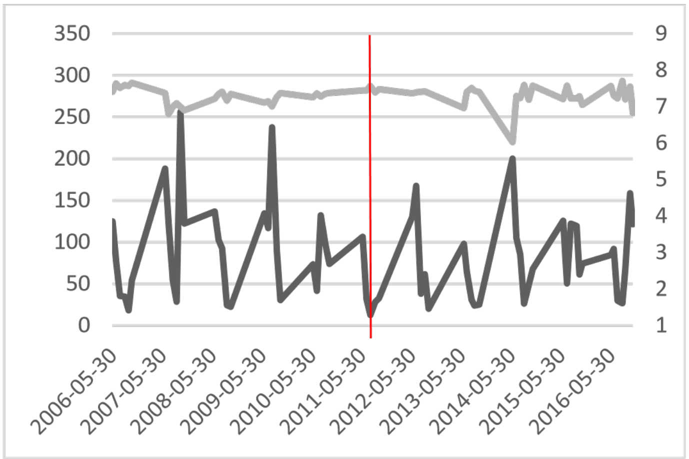
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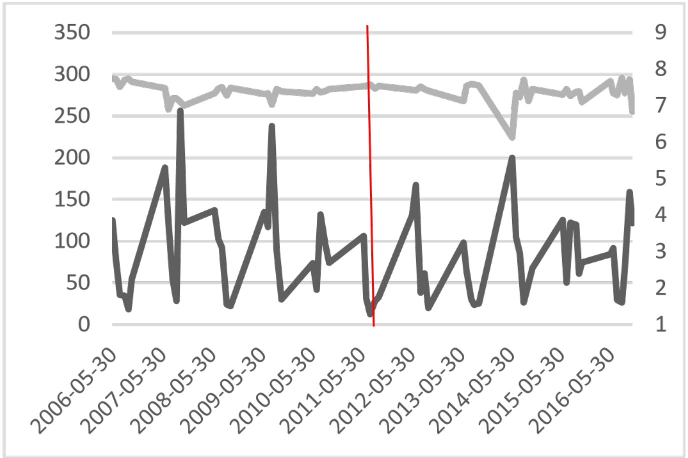
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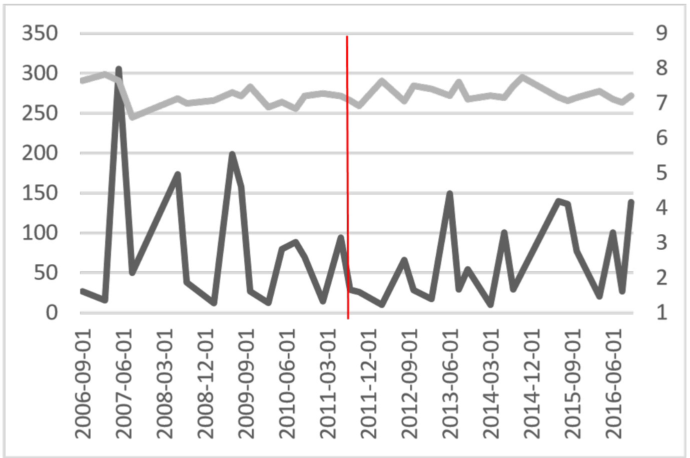
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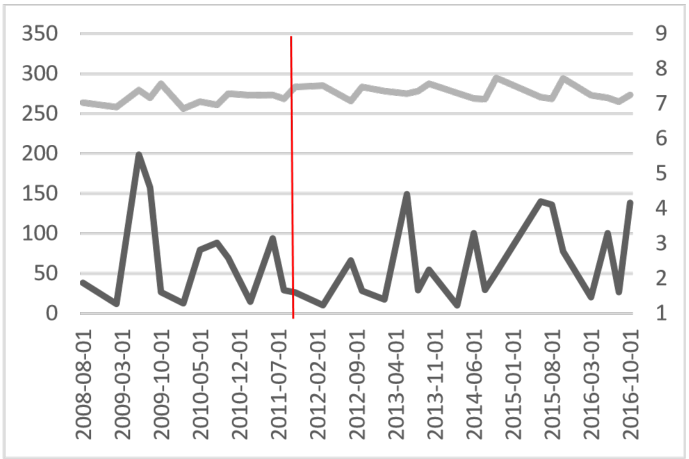
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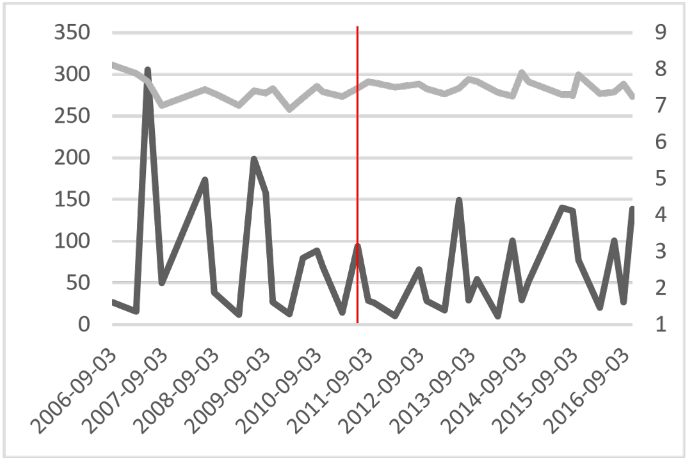
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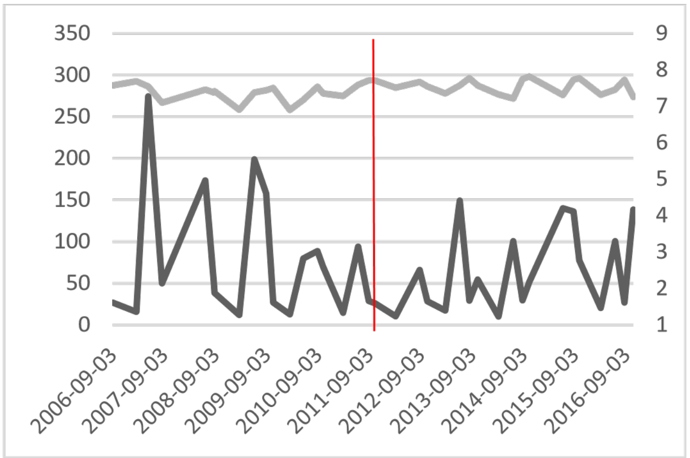
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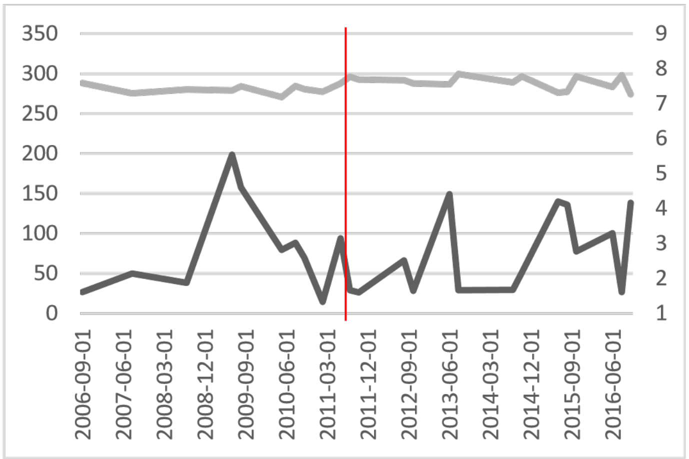
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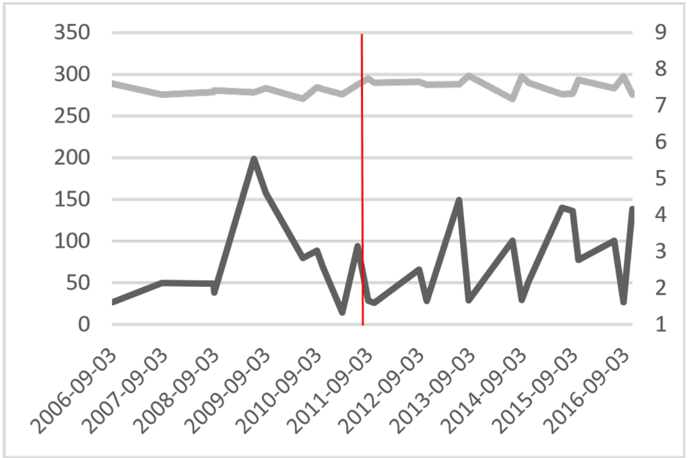
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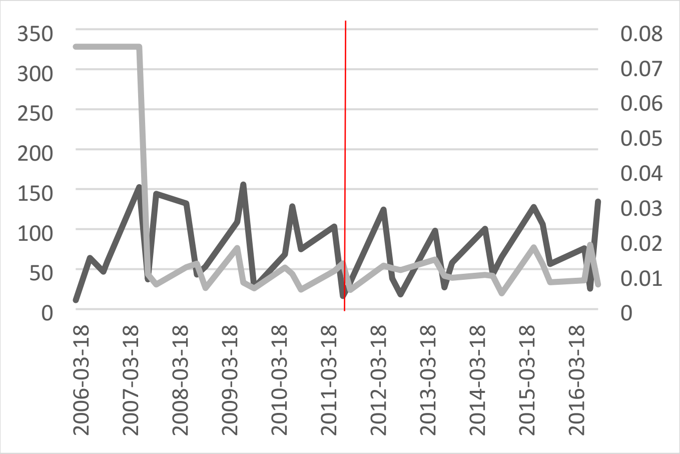
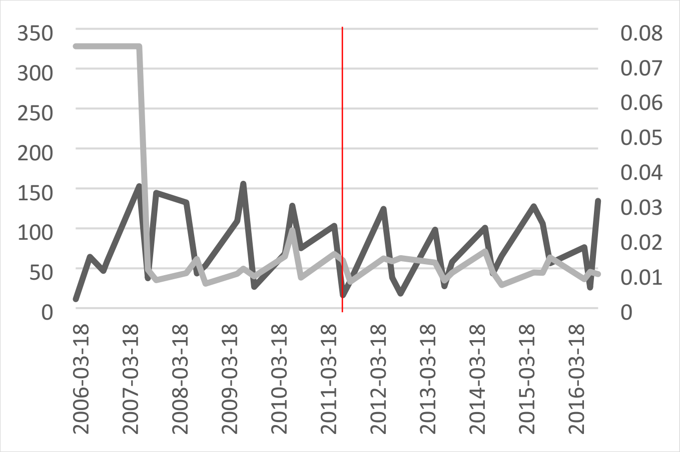
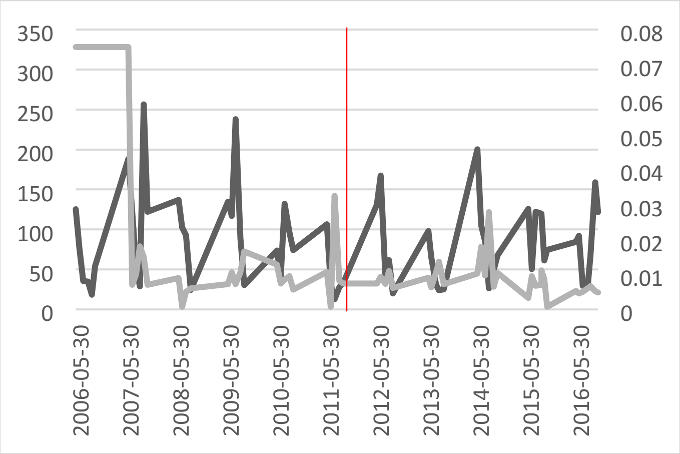
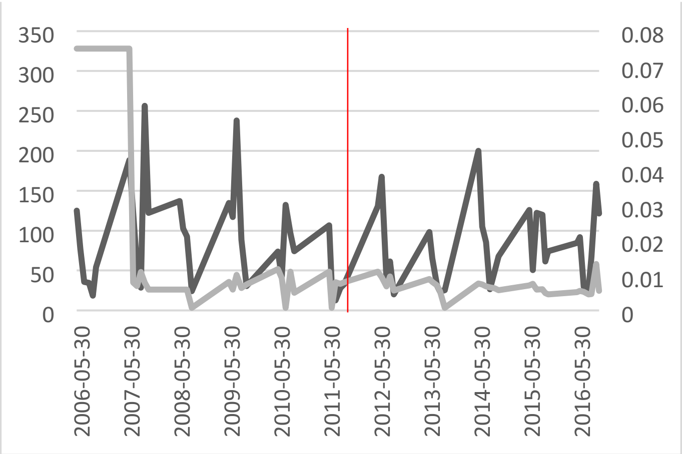
3. Total phosphorus, dark grey lines, right axis, and stream flow, light grey line, left axis. Vertical line displays the date of fire occurrence.





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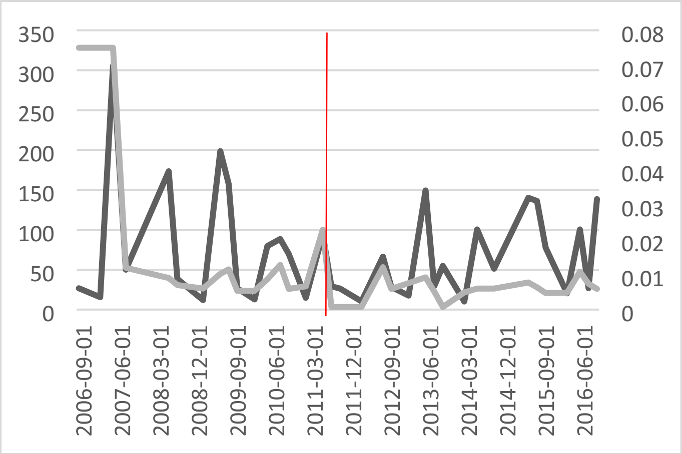
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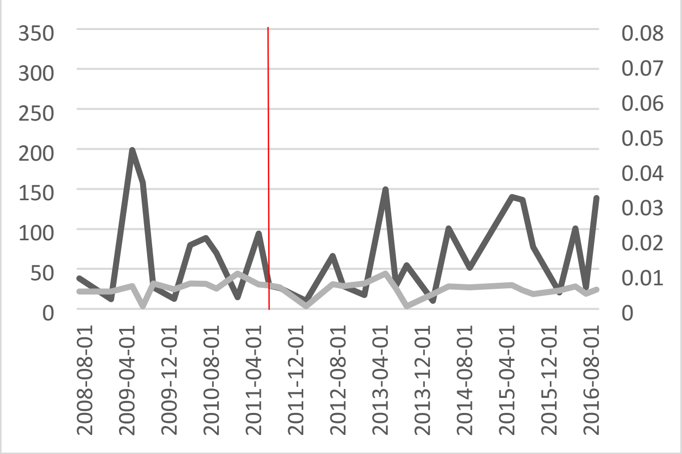
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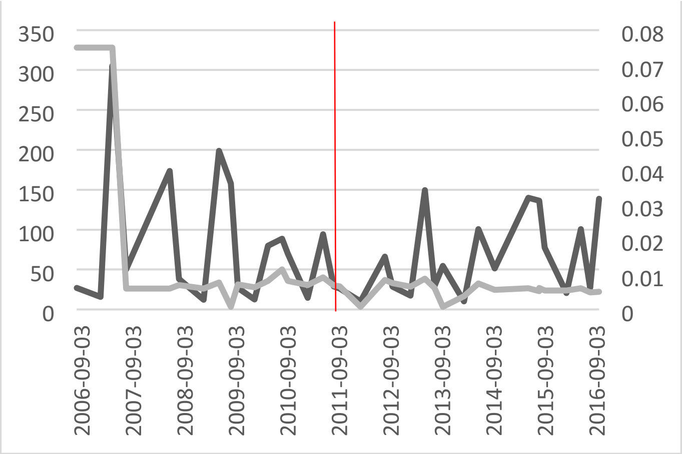
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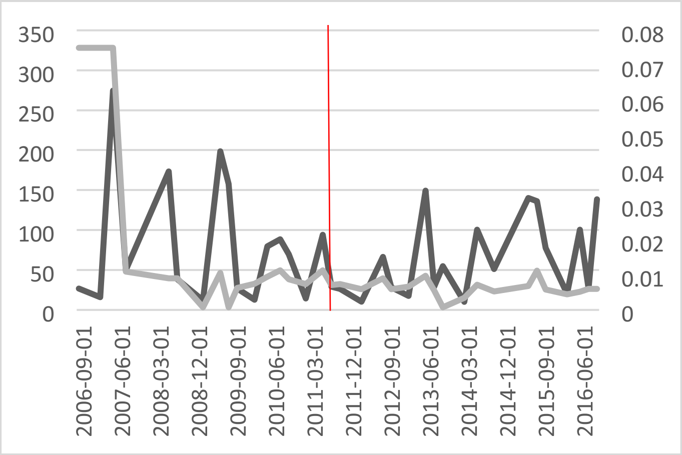
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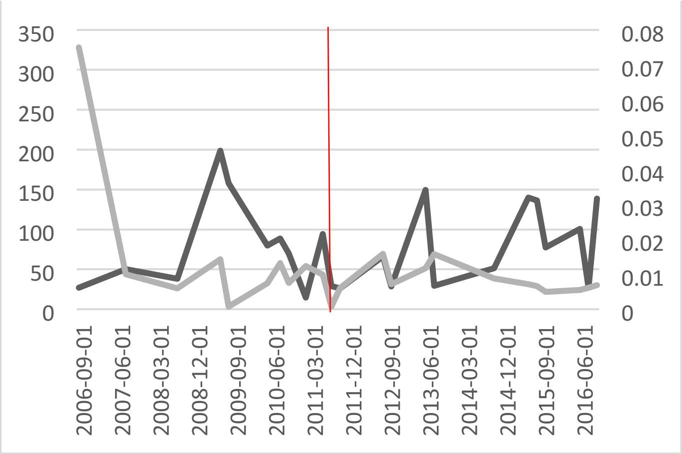
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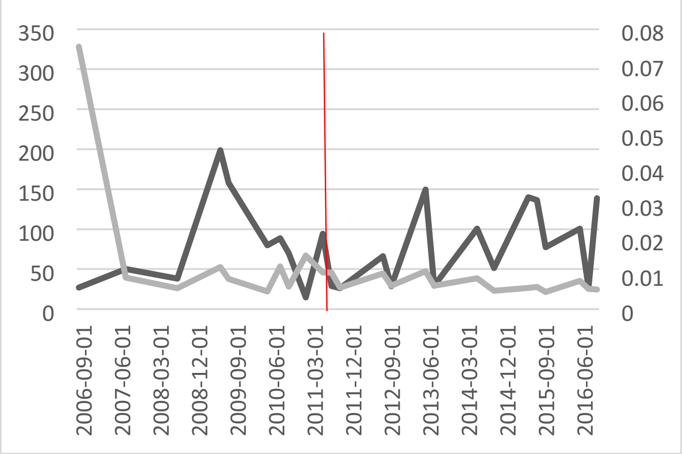

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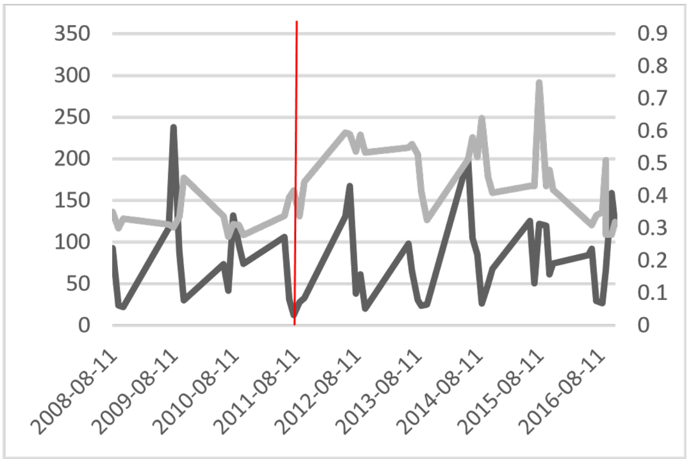

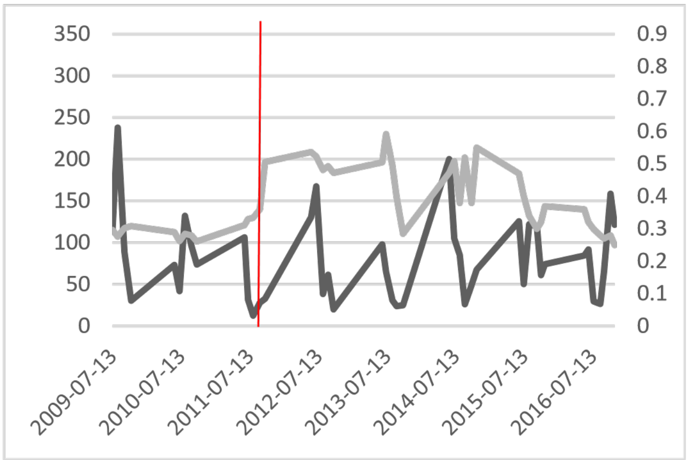

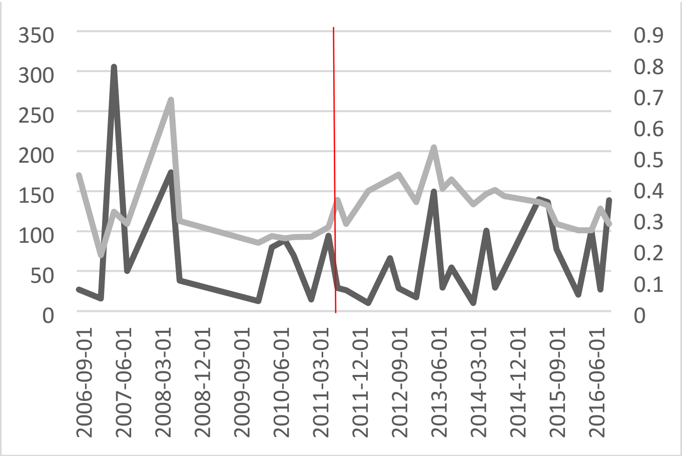
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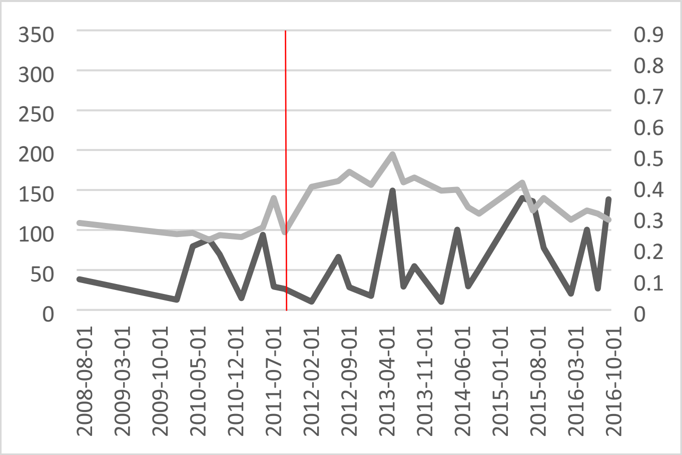
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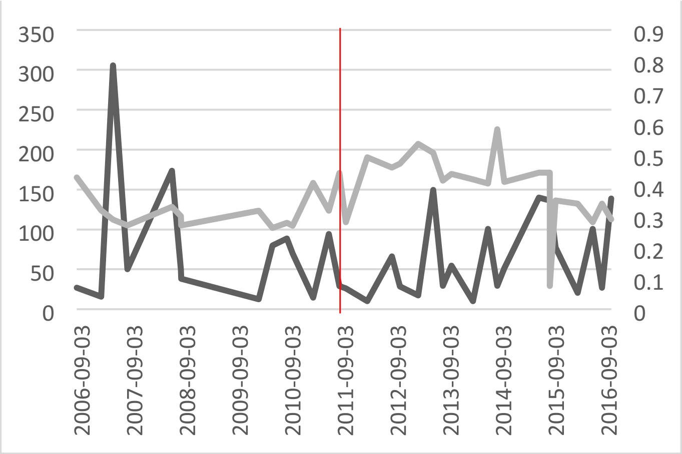
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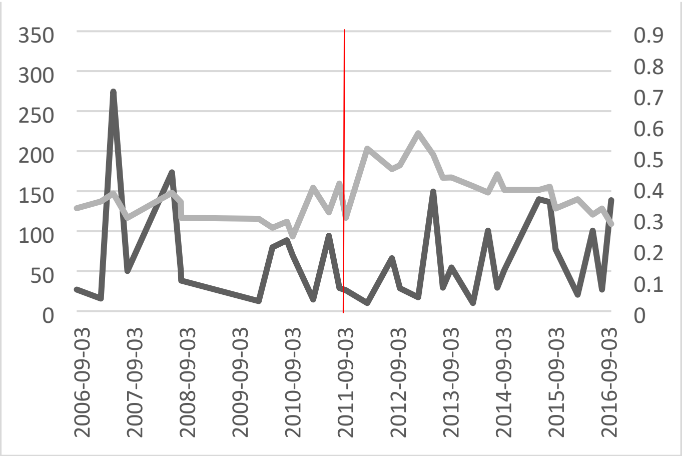
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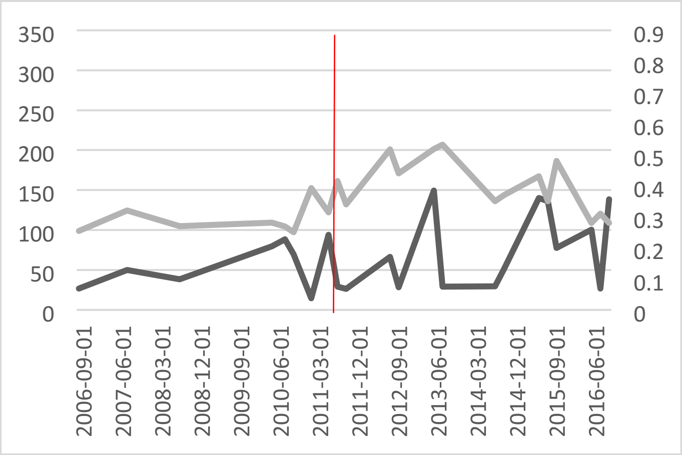
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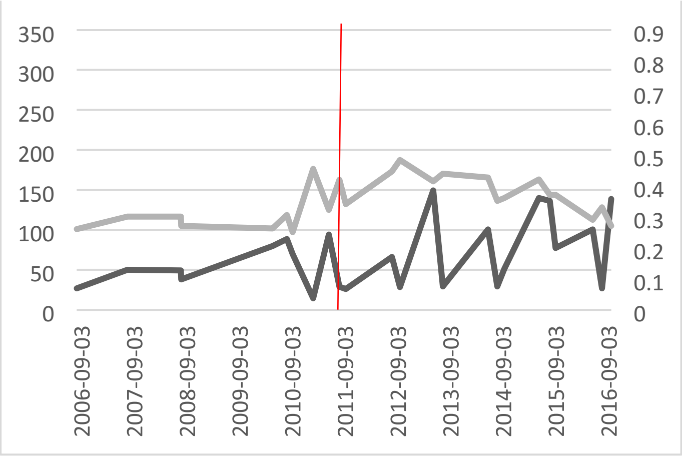
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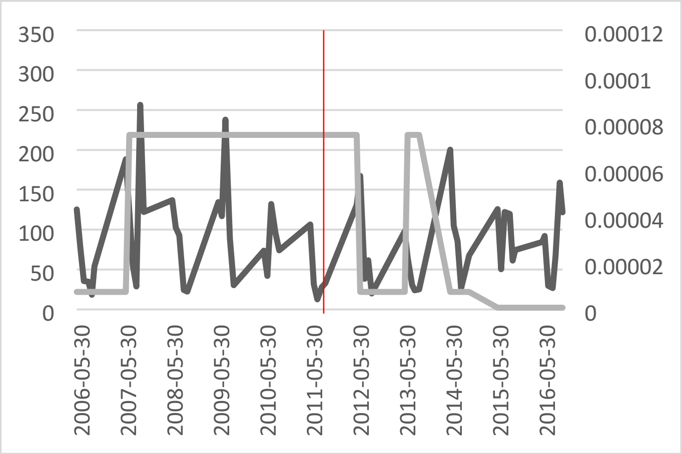
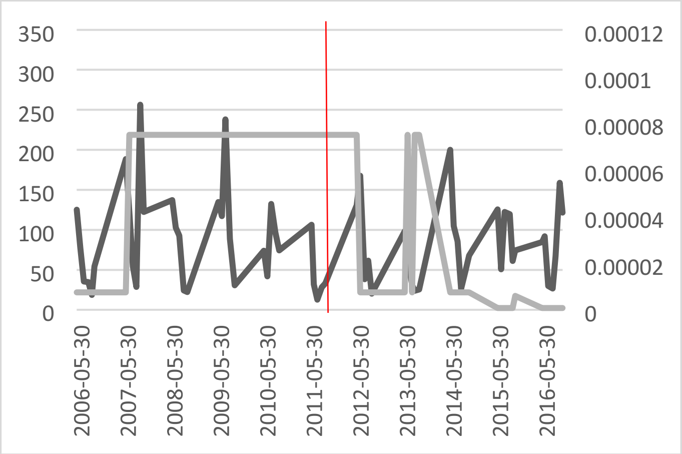
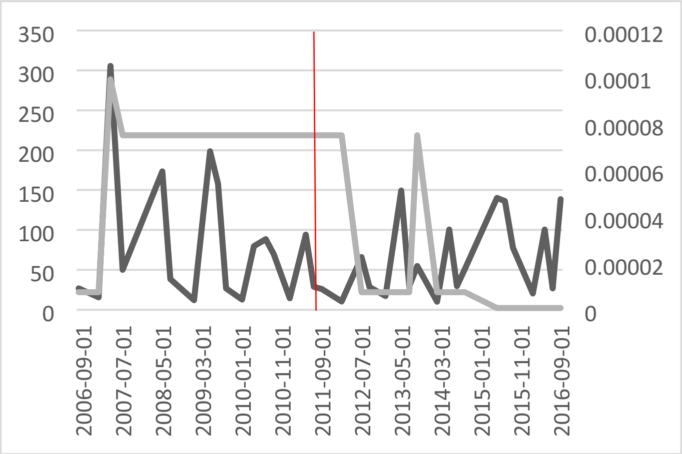
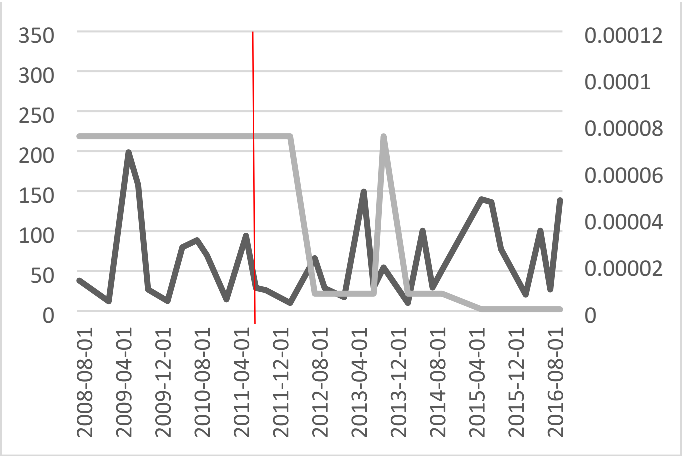
5. Mercury concentration, dark grey lines, right axis, and stream flow, light grey line, left axis. Vertical line displays the date of fire occurrence.





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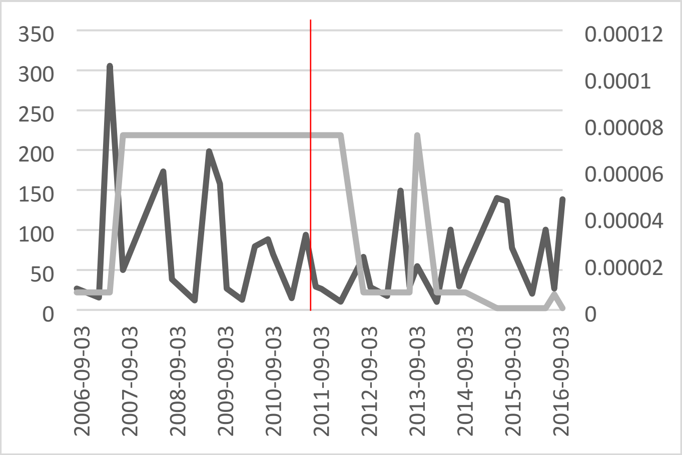
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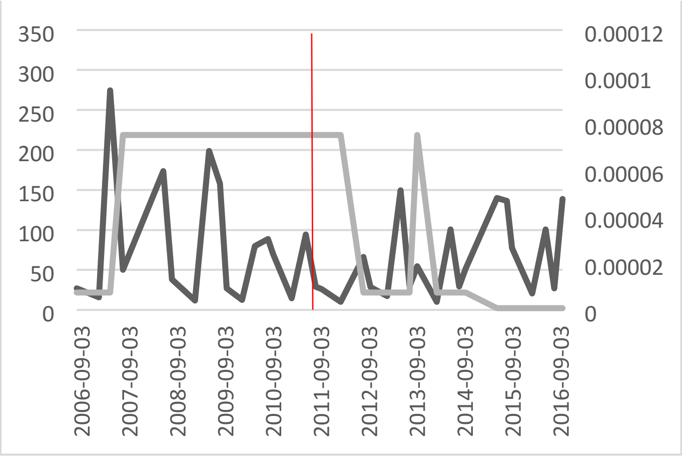
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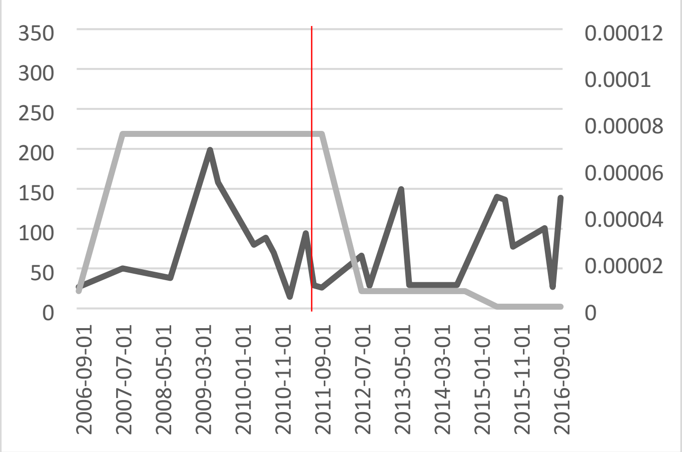
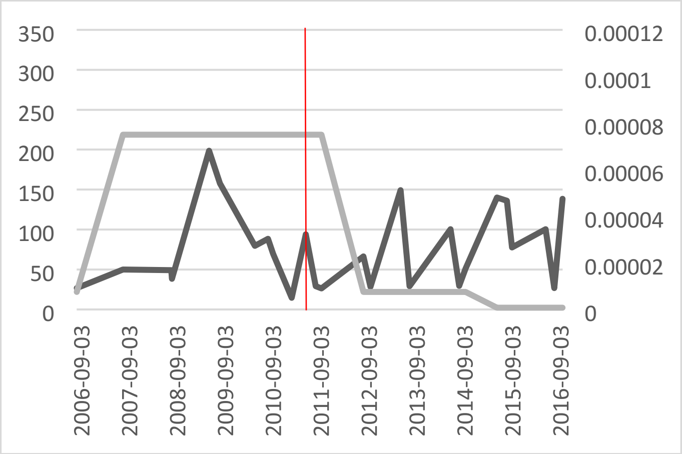
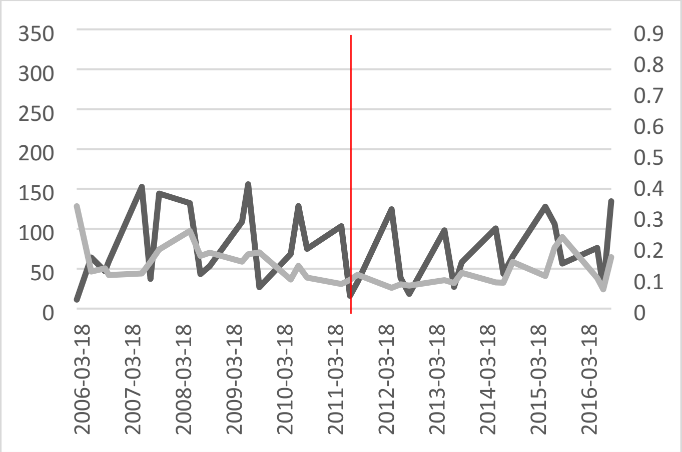
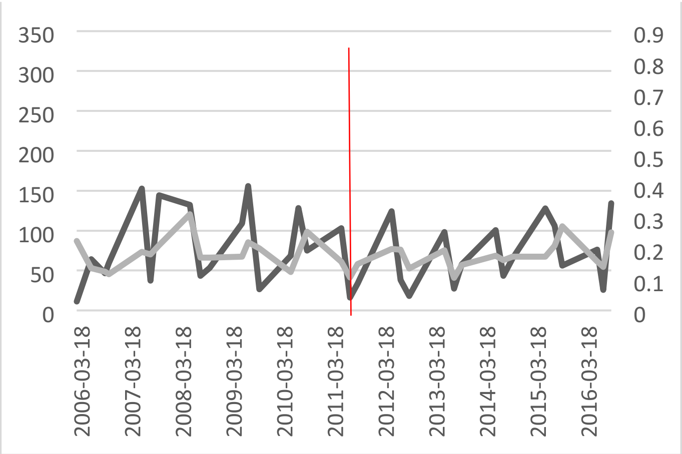




6. Iron concentration, dark grey lines, right axis, and stream flow, light grey line, left axis. Vertical line displays the date of fire occurrence.

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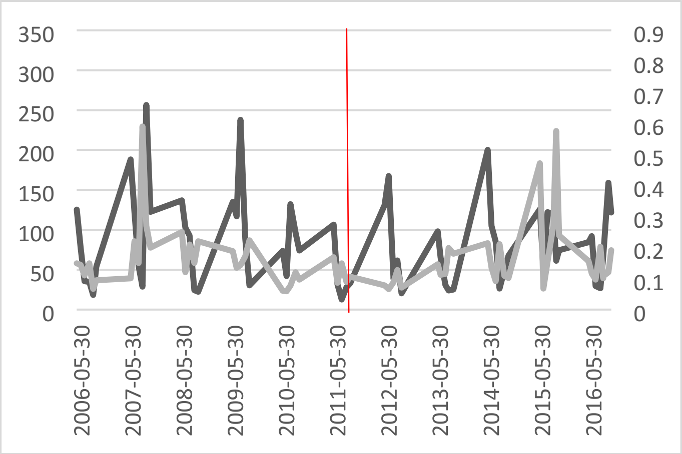
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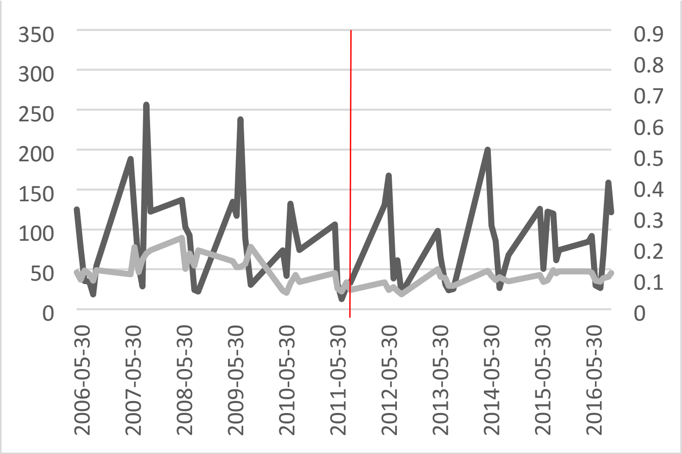
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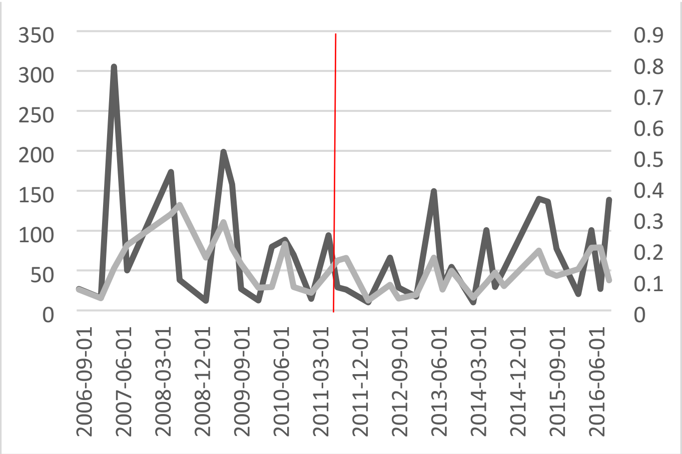
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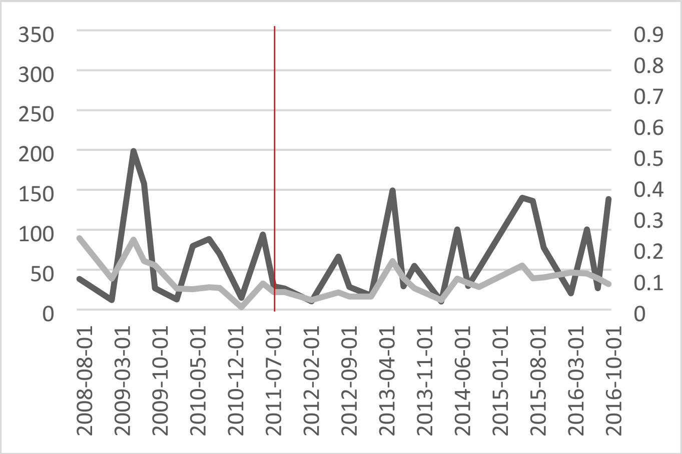
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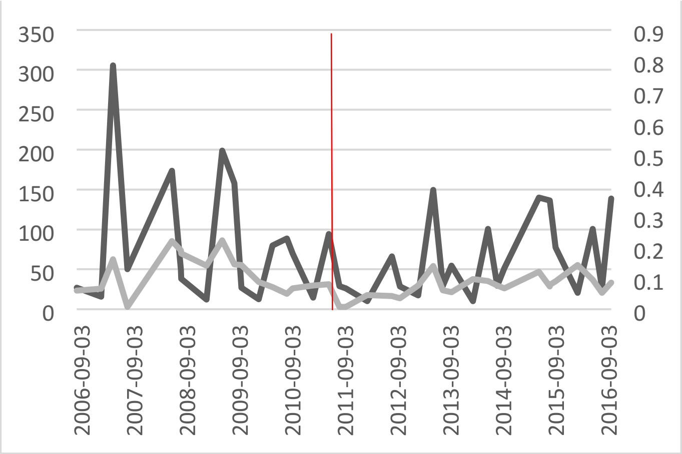
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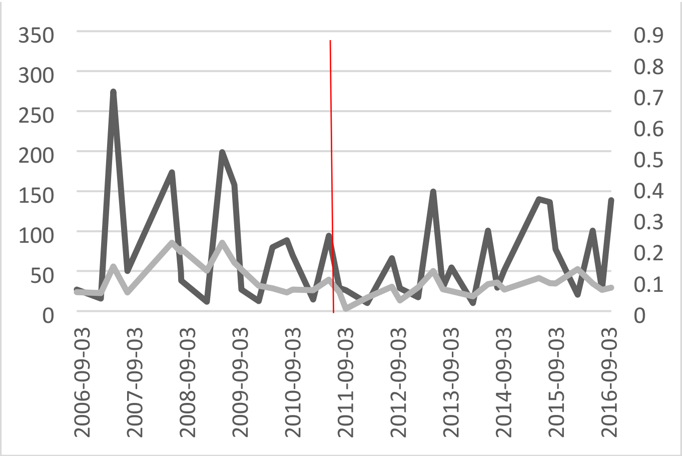
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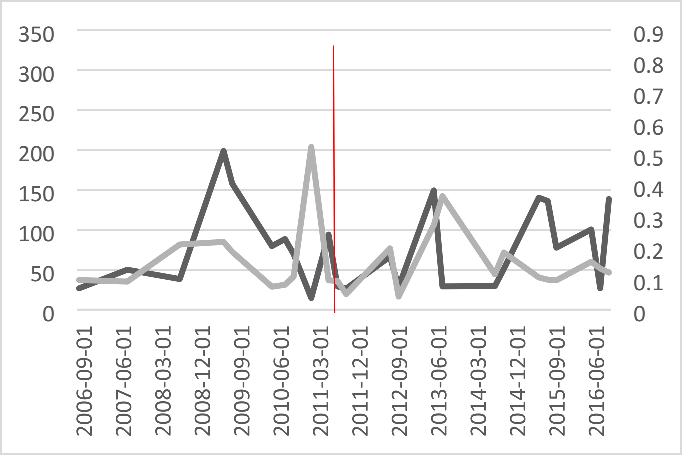
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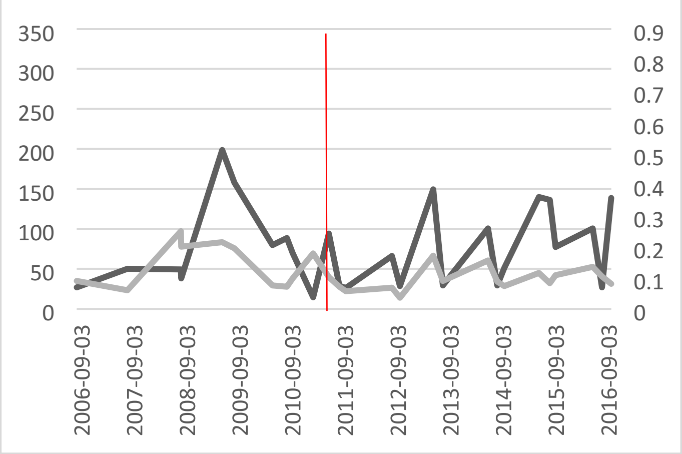
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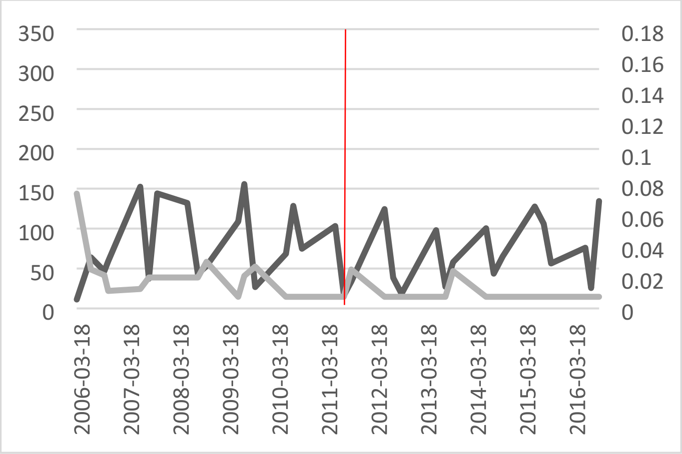
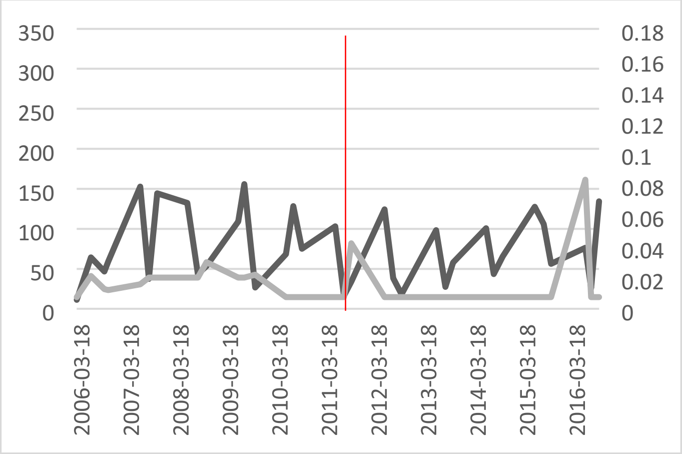
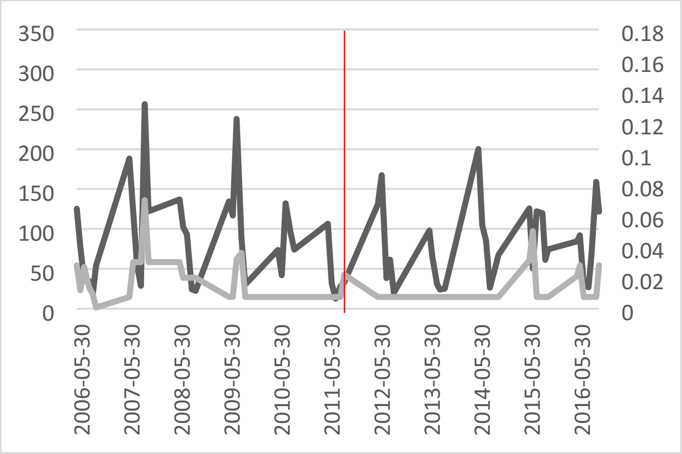
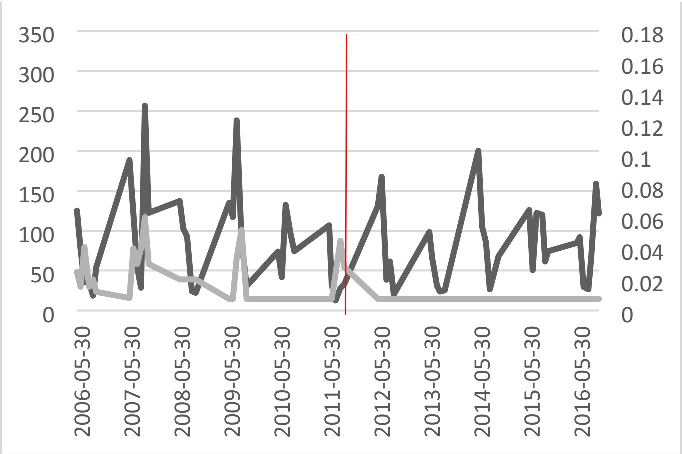
7. Ammonia variables, dark grey lines, right axis, and stream flow, light grey line, left axis. Vertical line displays the date of fire occurrence.





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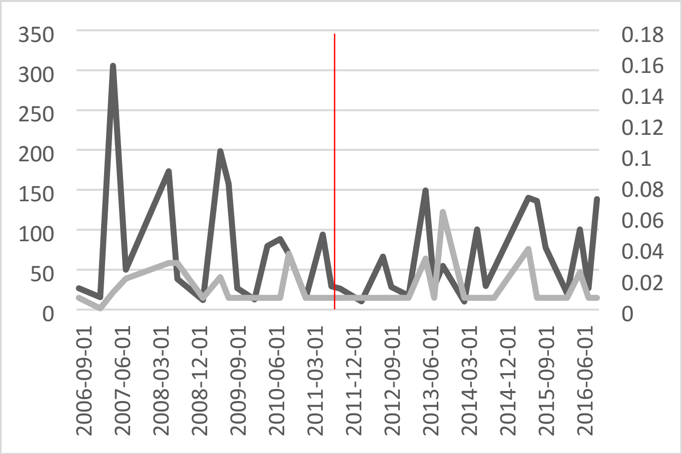
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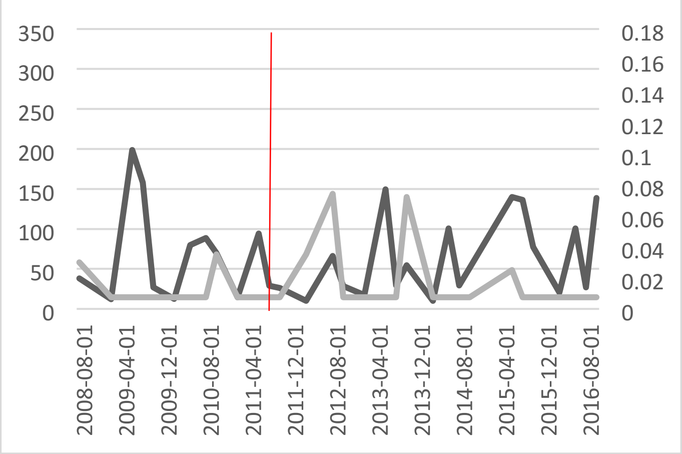
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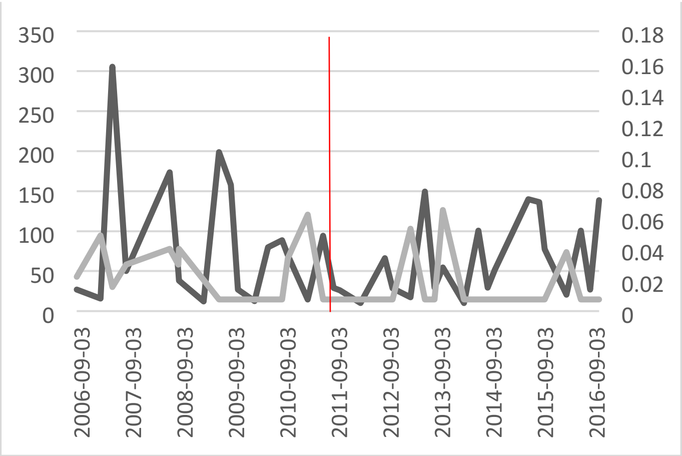
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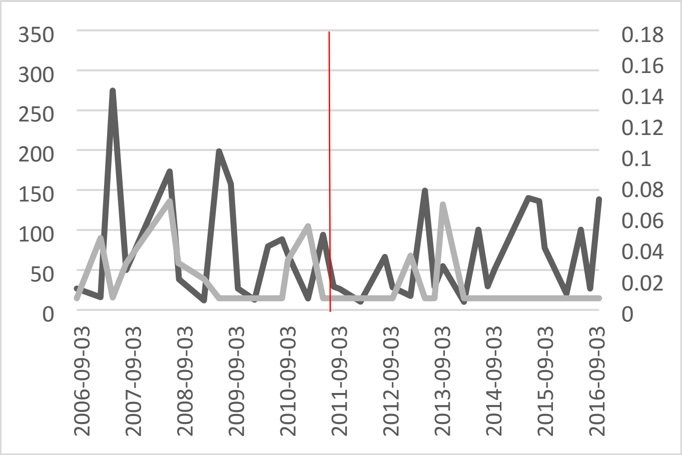
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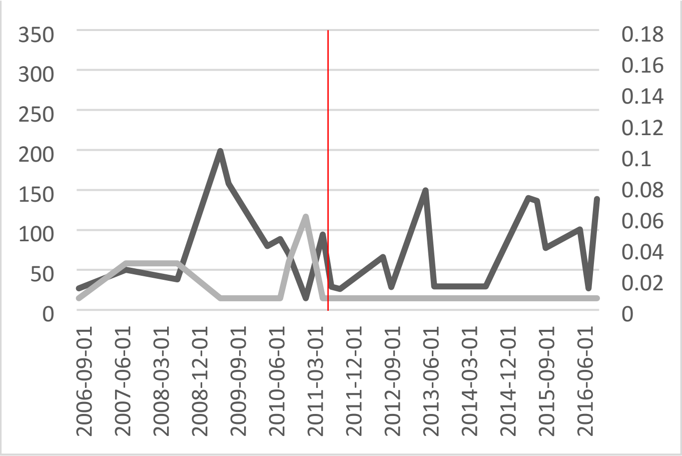
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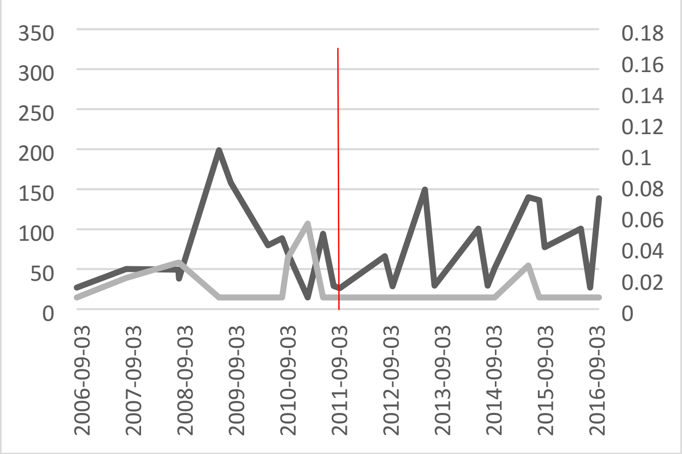

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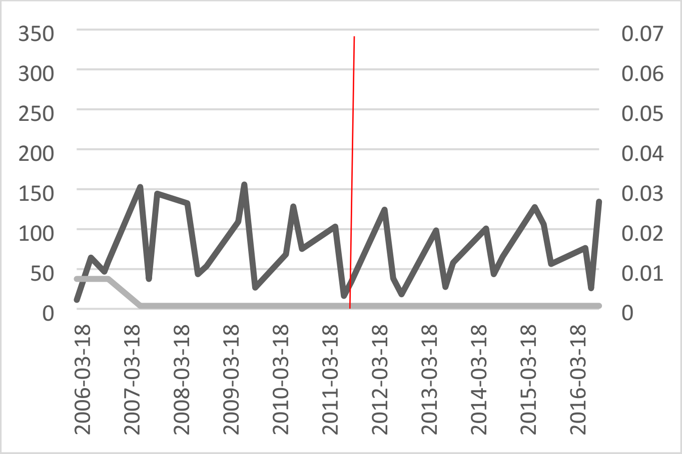

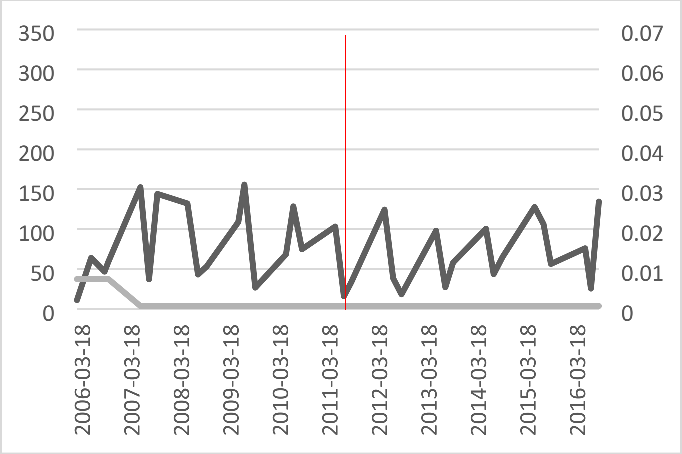

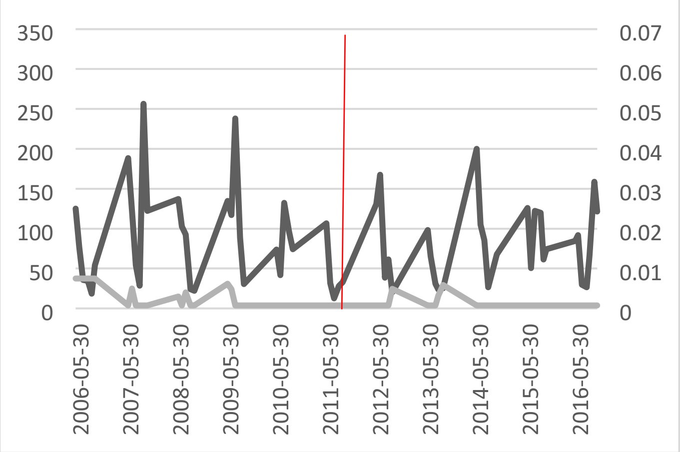
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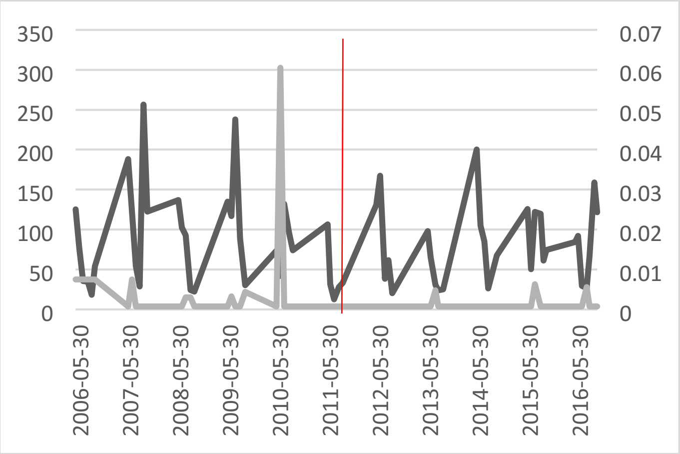
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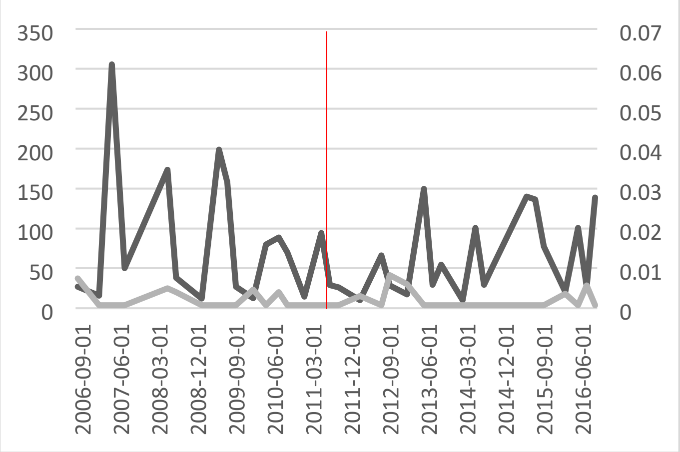
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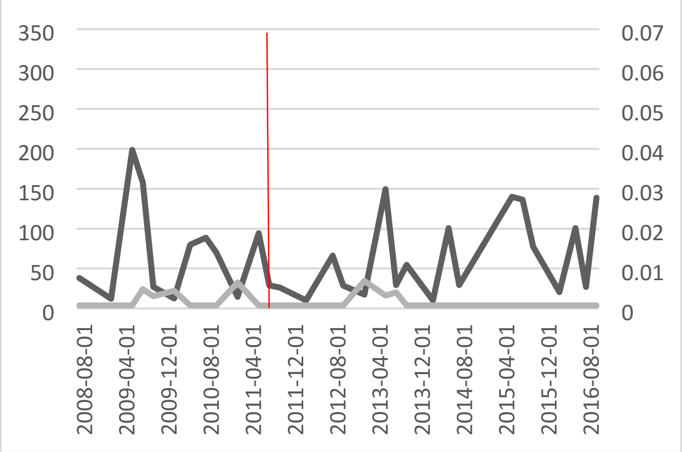
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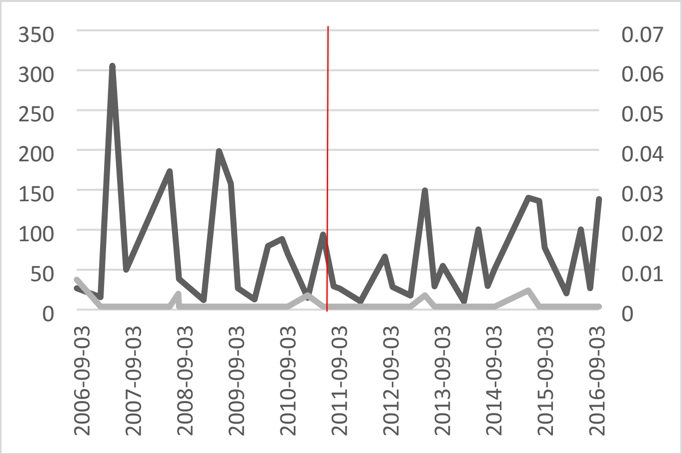
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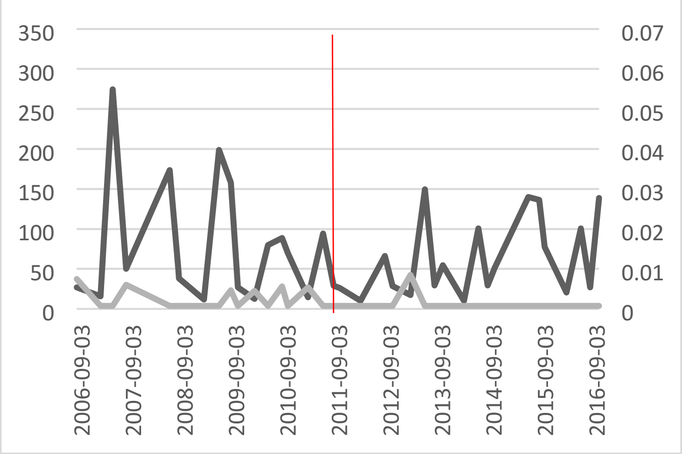
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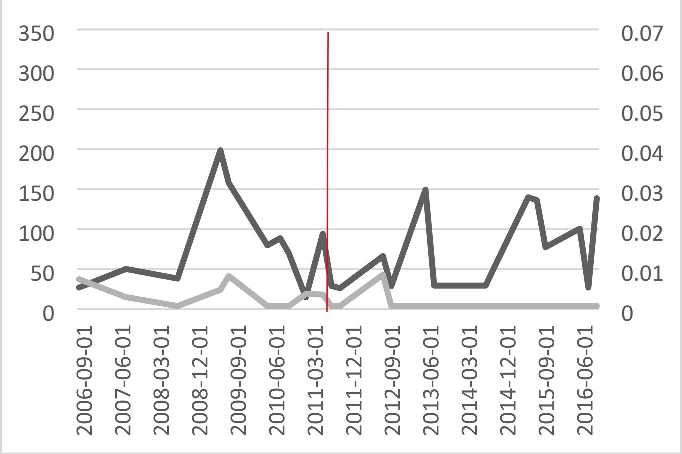
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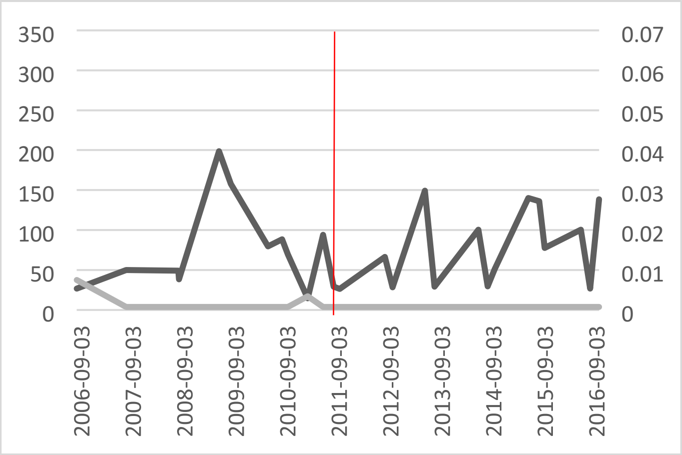
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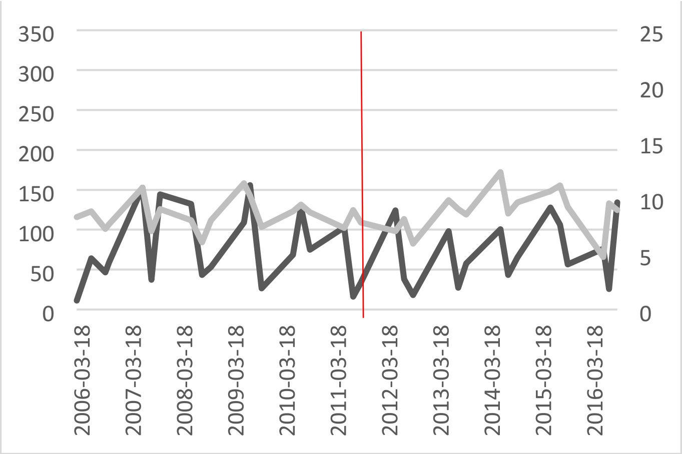
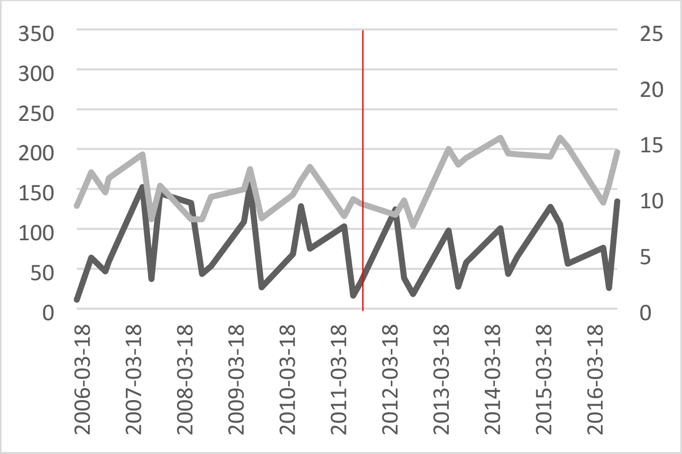
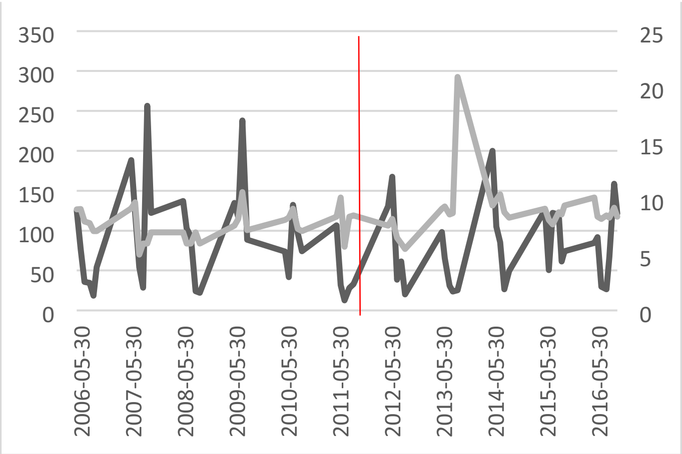
APPENDIX II

Downstream Graphs, i.e., downstream of the mine site.

1. Dissolved organic carbon, dark grey lines, right axis, and stream flow, light grey line, left axis. Vertical line displays the date of fire occurrence.



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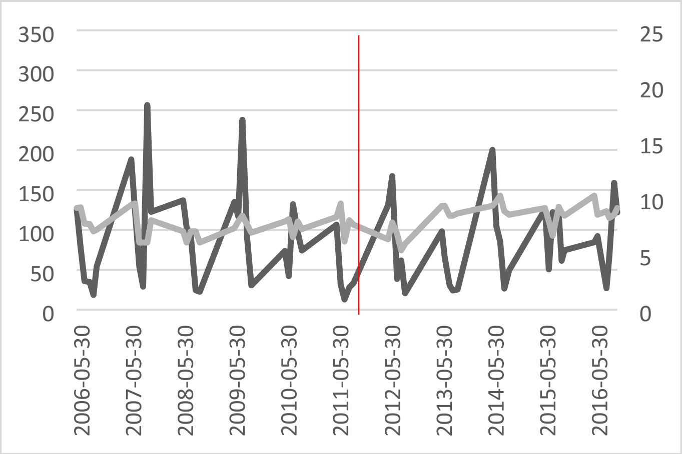
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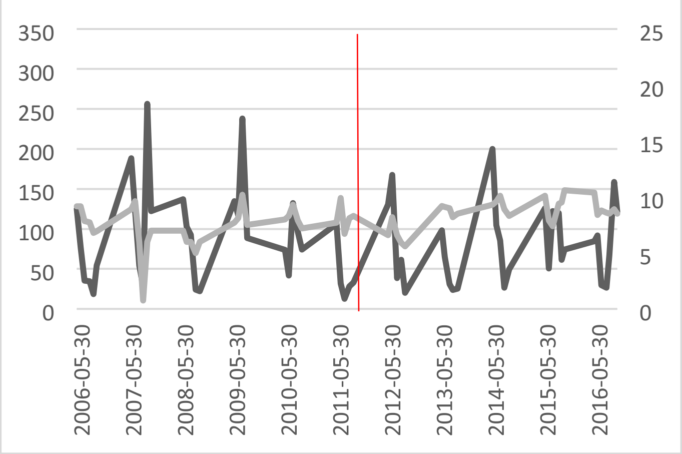
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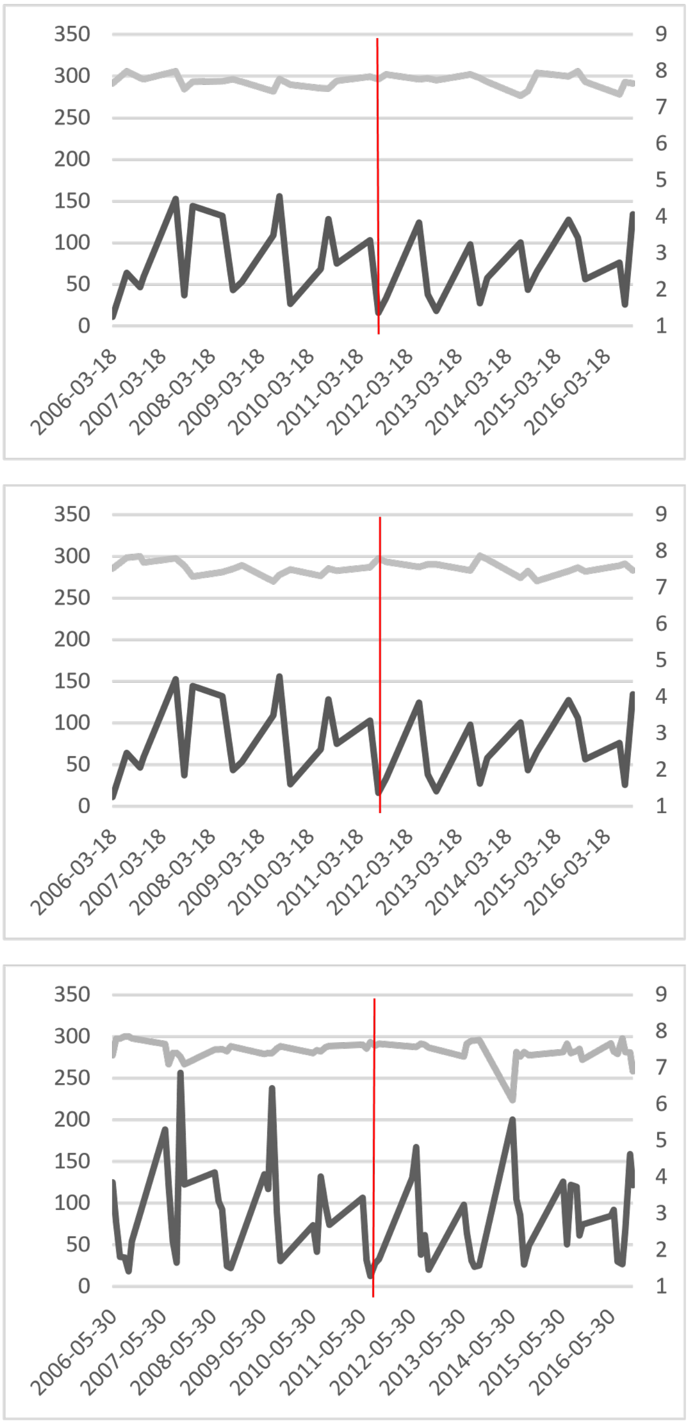
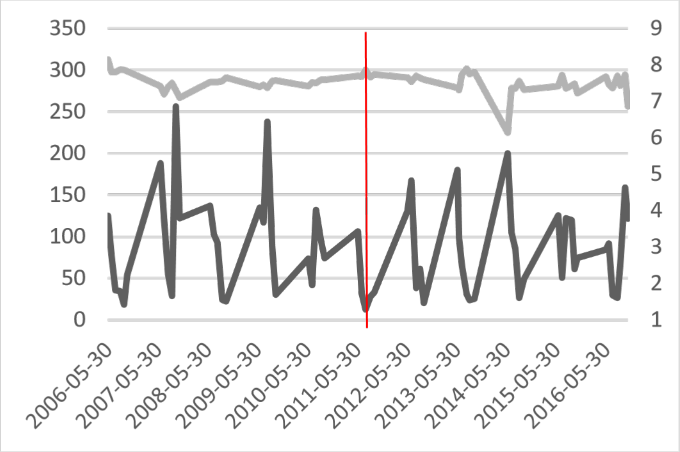
2016-05-30

2. pH, dark grey lines, right axis, and stream flow, light grey line, left axis. Vertical line displays the date of fire occurrence.

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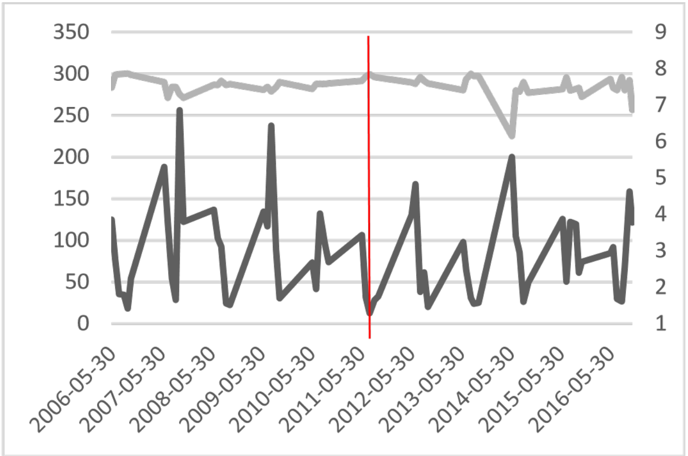
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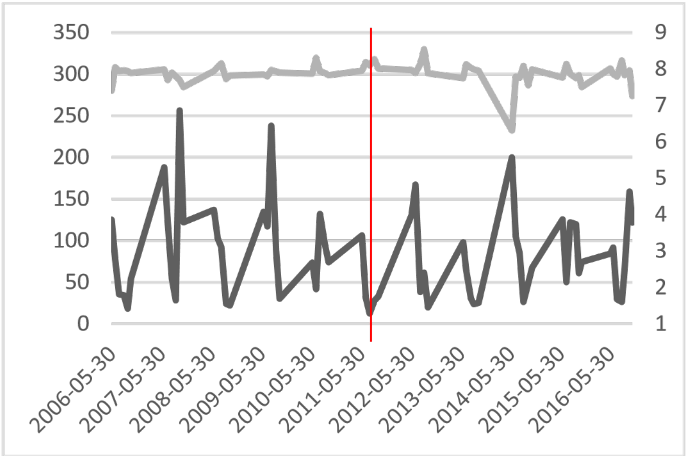
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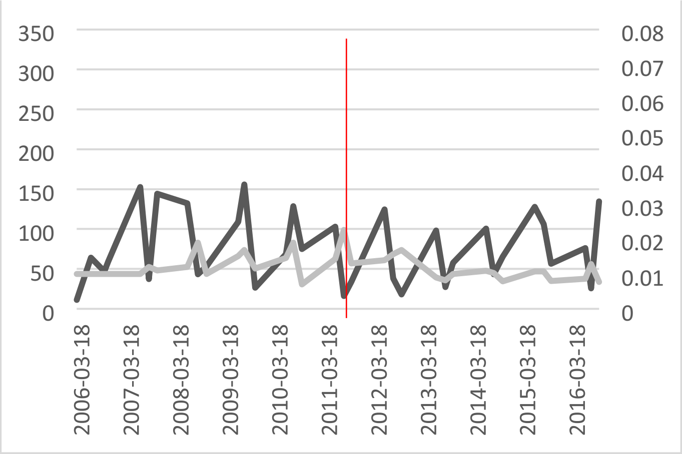
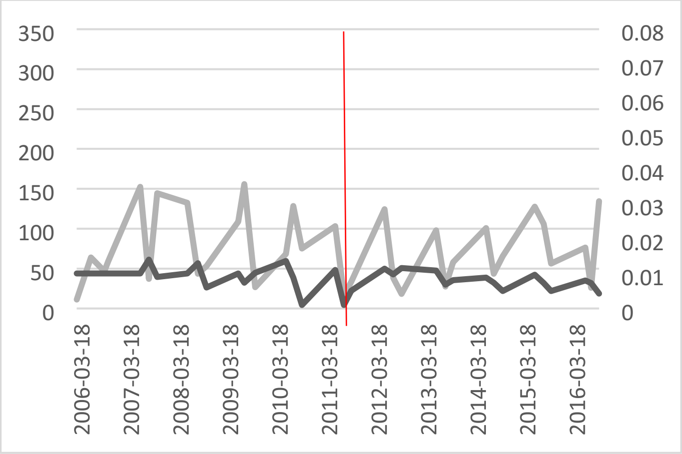
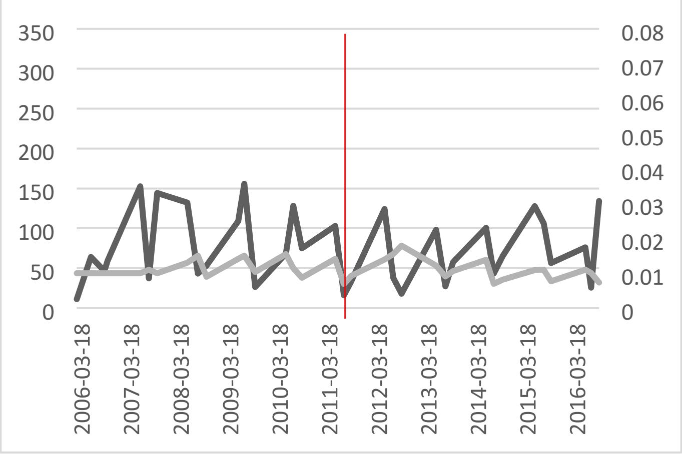
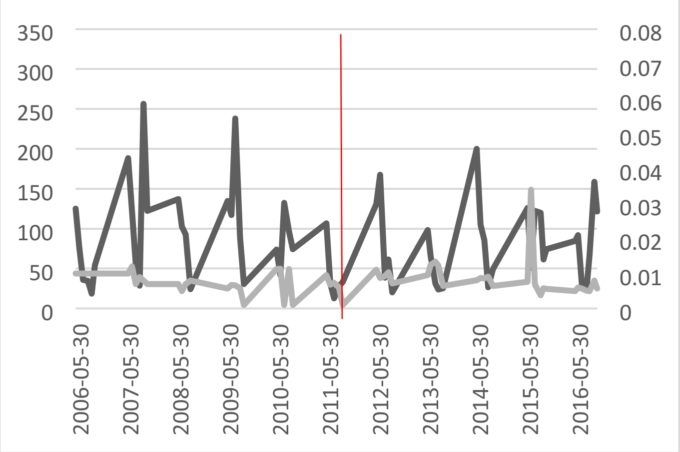
3. Total phosphorus, dark grey lines, right axis, and stream flow, light grey line, left axis. Vertical line displays the date of fire occurrence.





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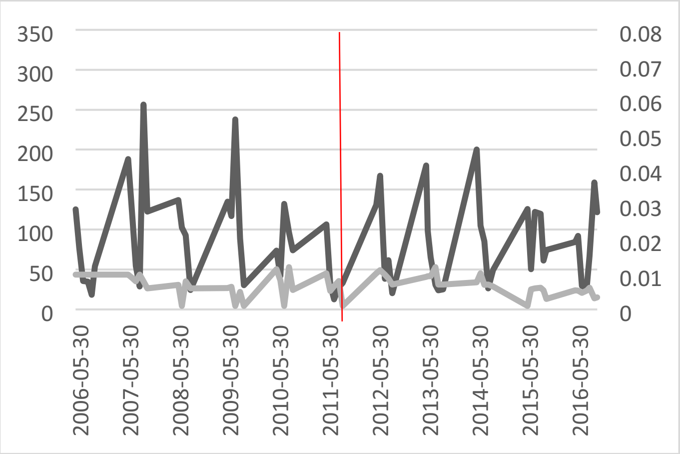
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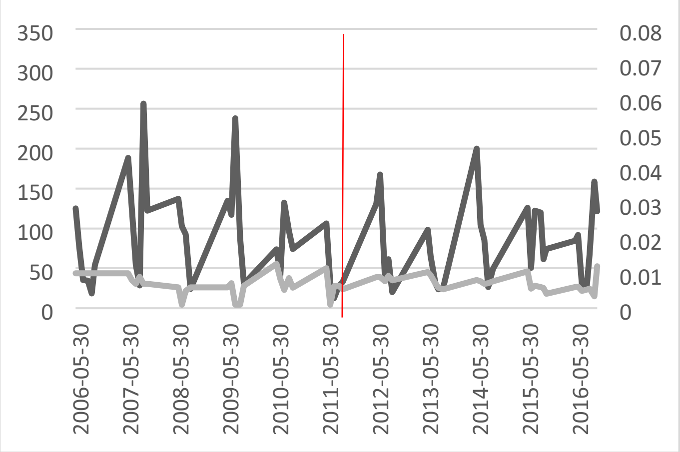
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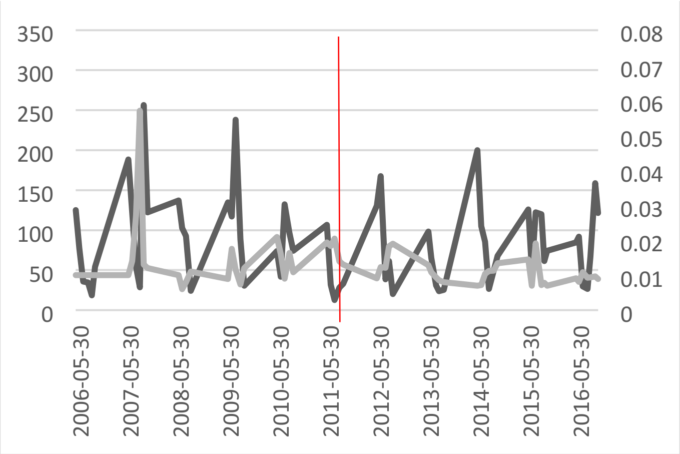
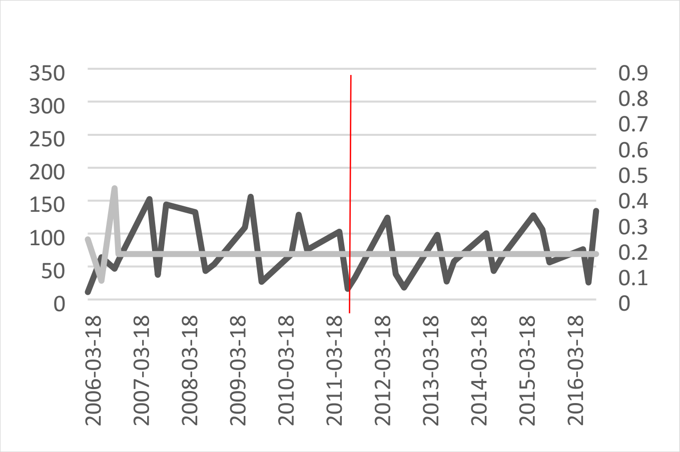
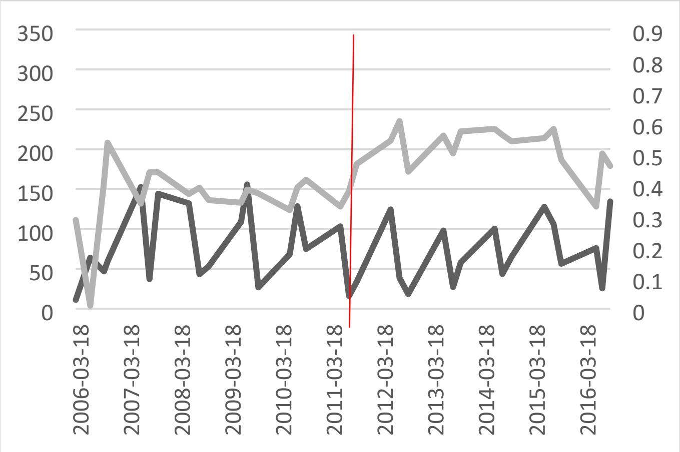
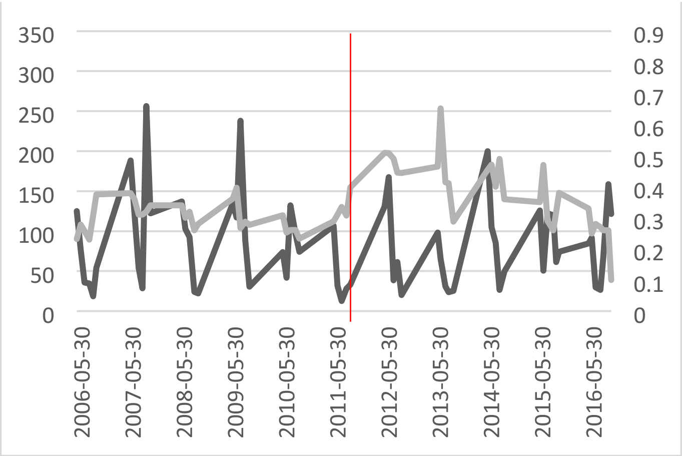


4. Total Kjeldahl nitrogen, dark grey lines, right axis, and stream flow, light grey line, left axis. Vertical line displays the date of fire occurrence.



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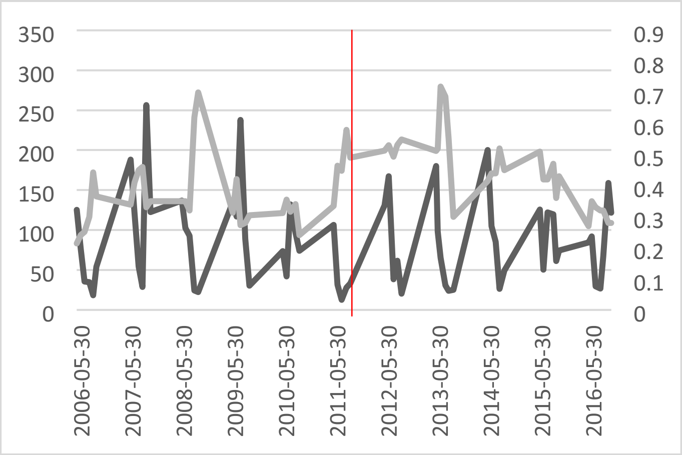
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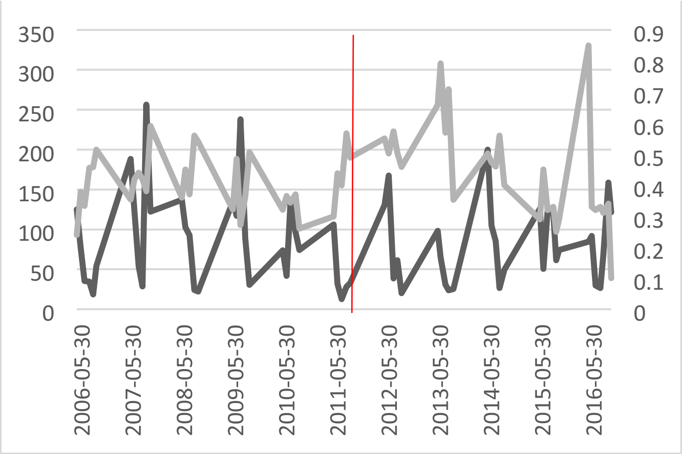
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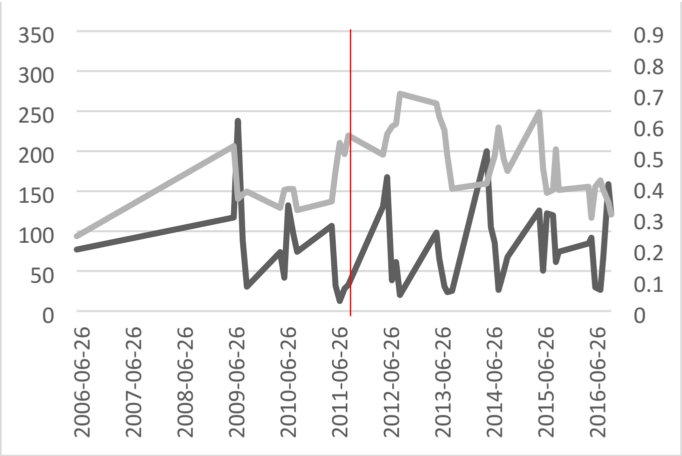
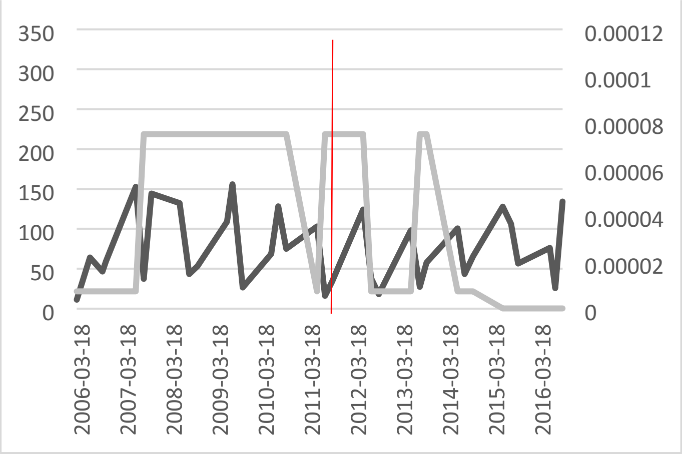
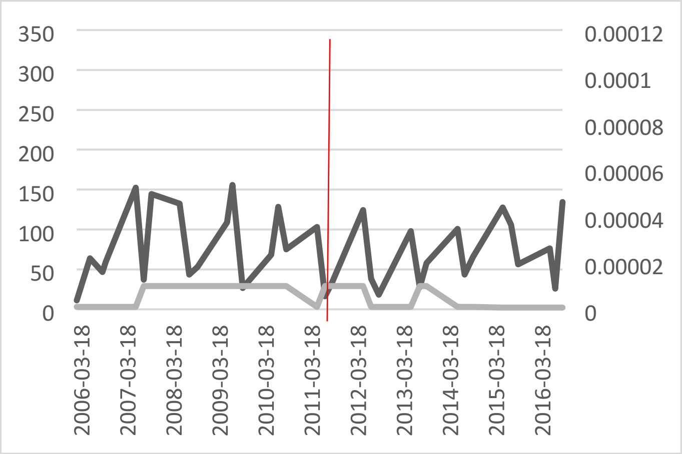
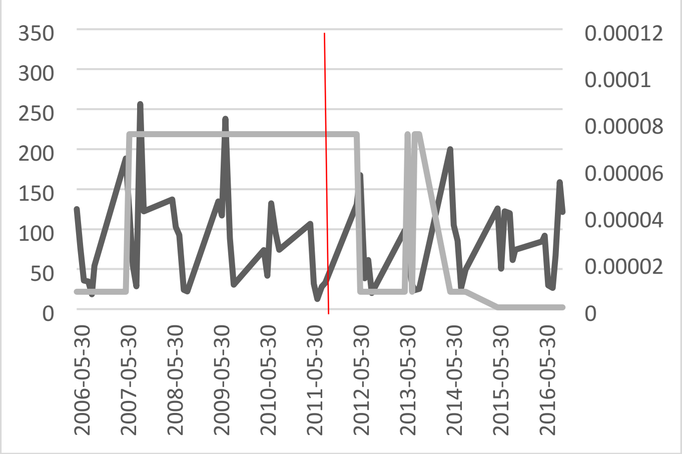


5. Mercury concentration, dark grey lines, right axis, and stream flow, light grey line, left axis. Vertical line displays the date of fire occurrence.



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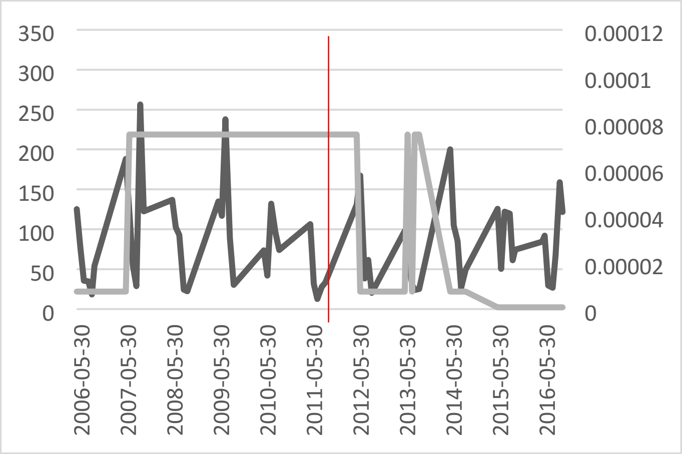
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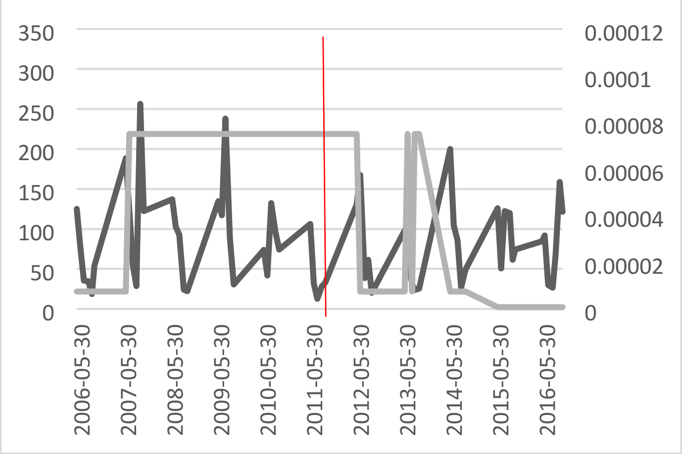
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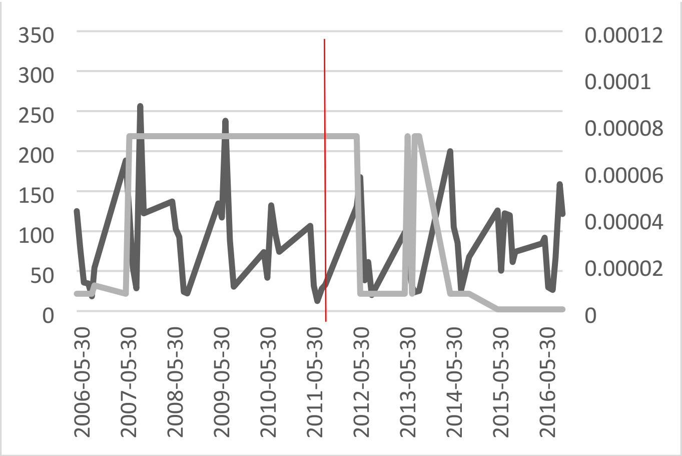
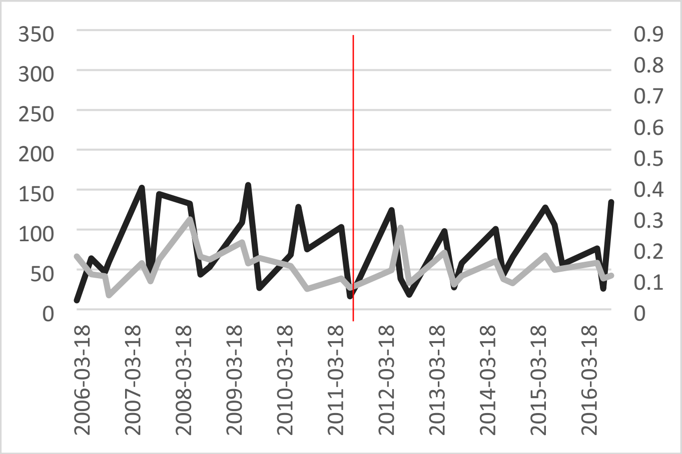
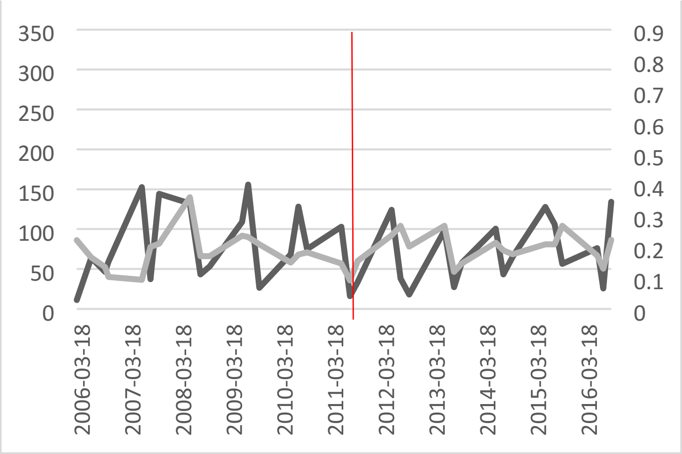
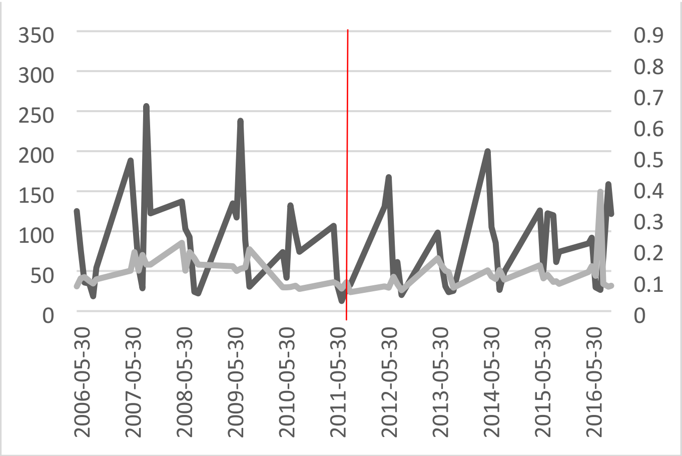


6. Iron concentration, dark grey lines, right axis, and stream flow, light grey line, left axis. Vertical line displays the date of fire occurrence.



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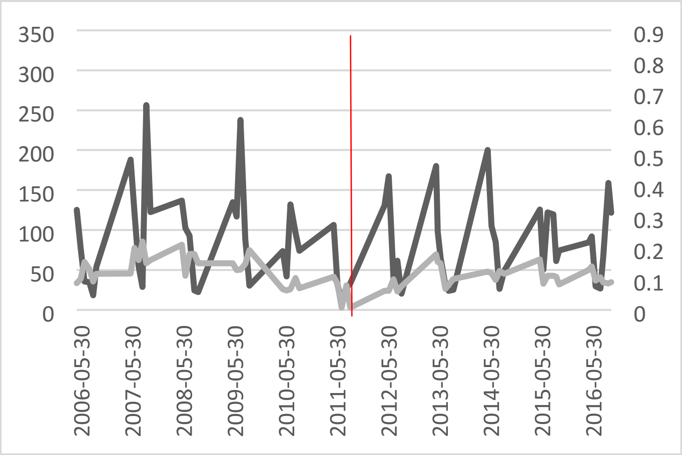
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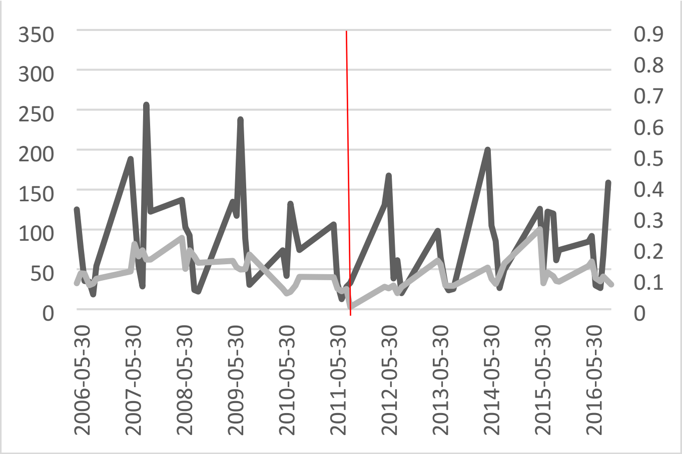
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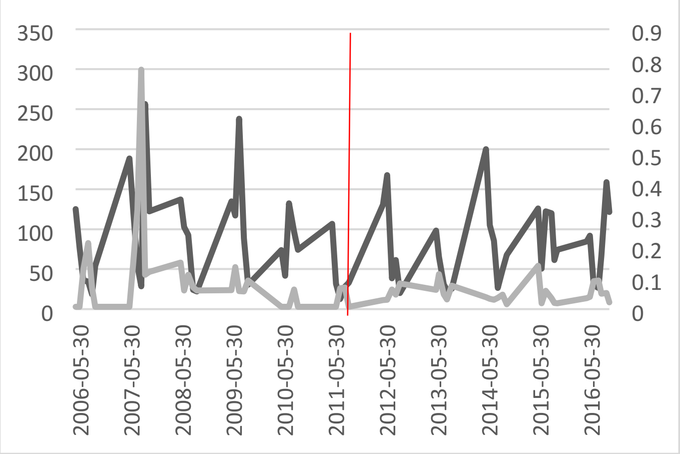
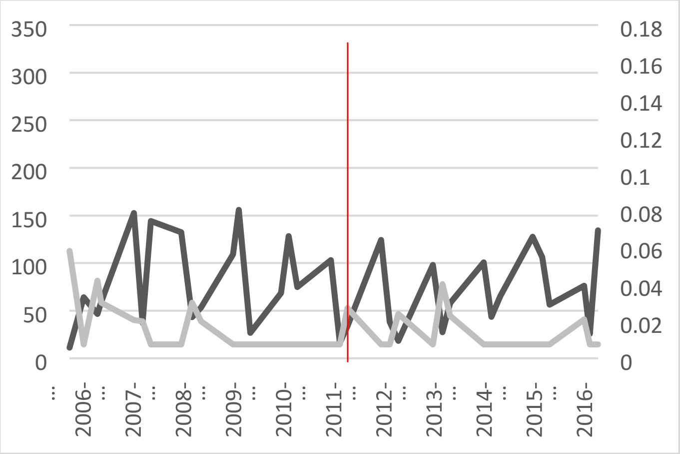
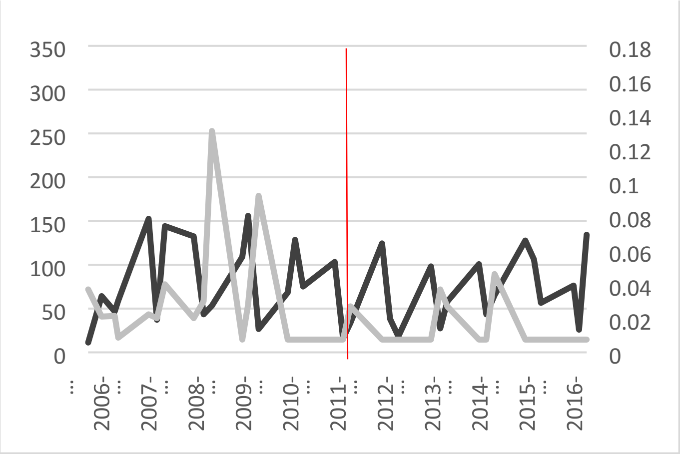
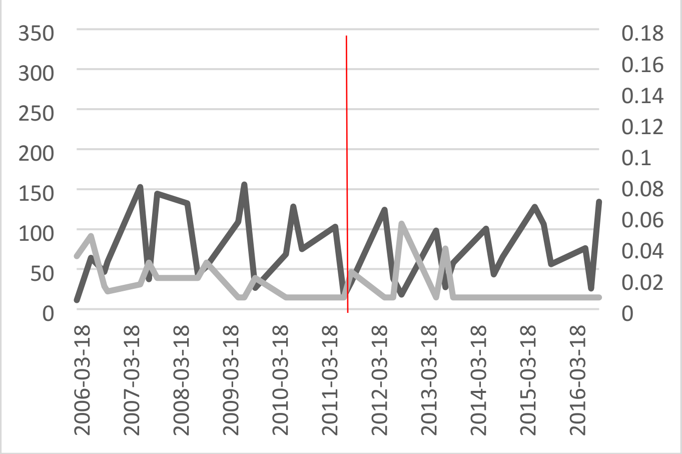


7. Ammonia concentration, dark grey lines, right axis, and stream flow, light grey line, left axis. Vertical line displays the date of fire occurrence.



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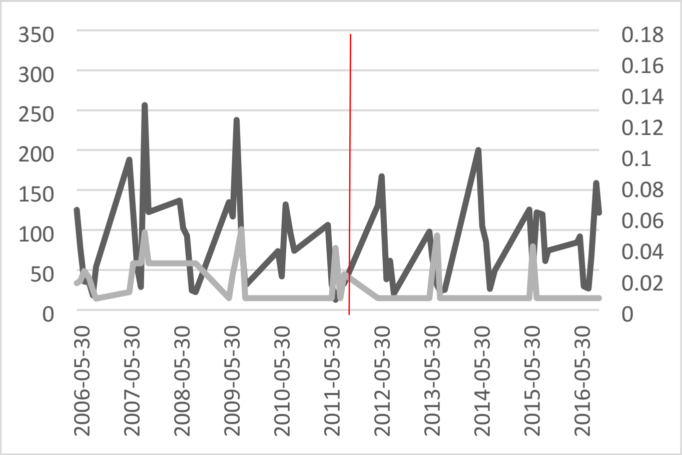
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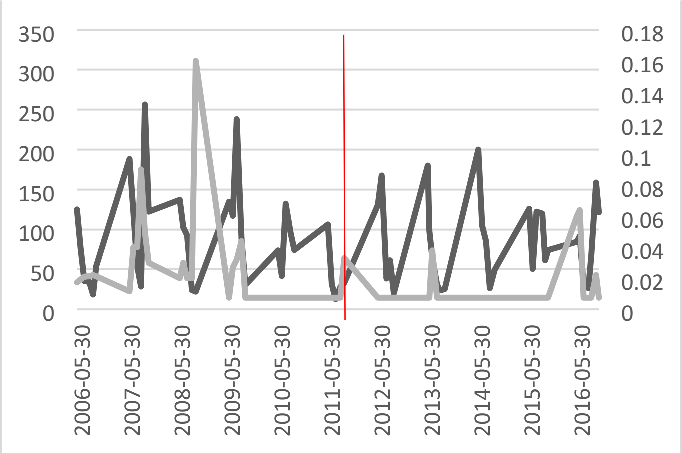
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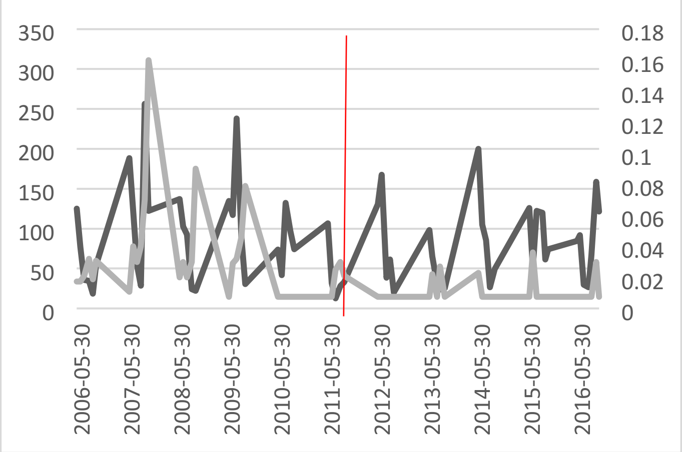
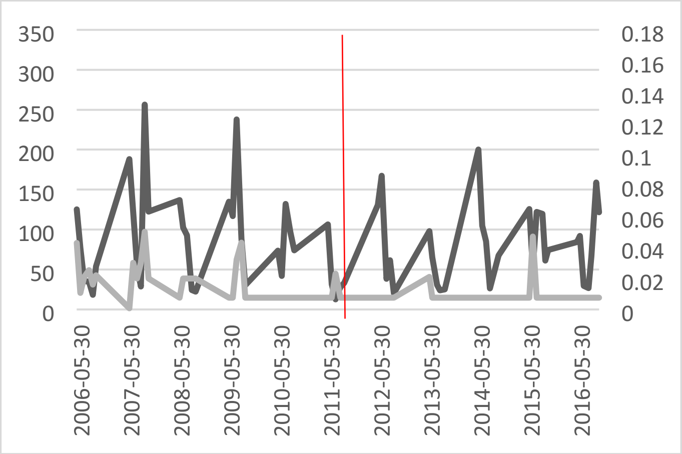
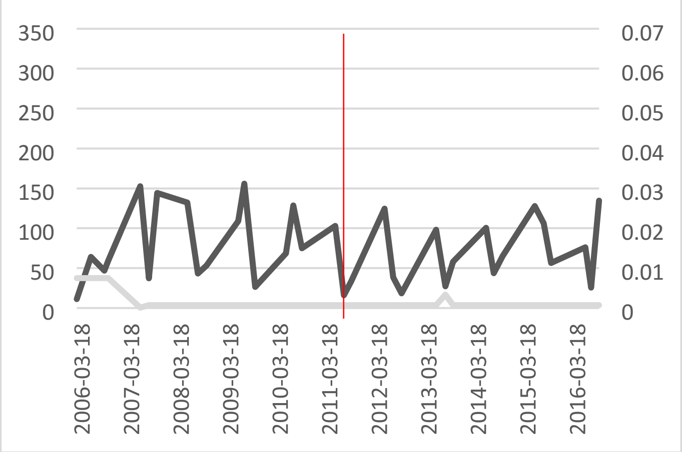
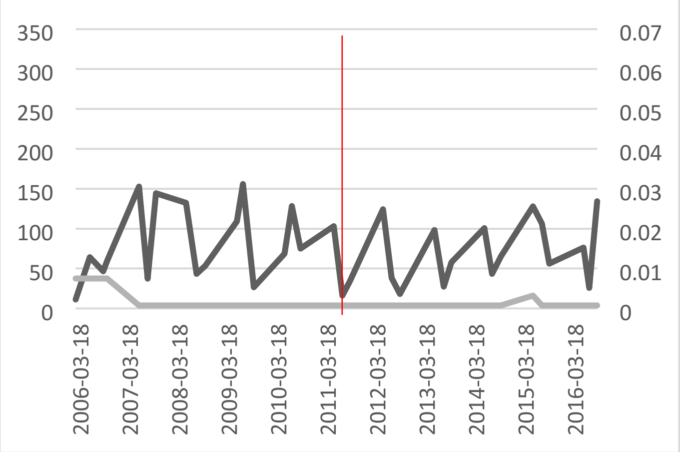




8. Zinc concentration, dark grey lines, right axis, and stream flow, light grey line, left axis. Vertical line displays the date of fire occurrence.

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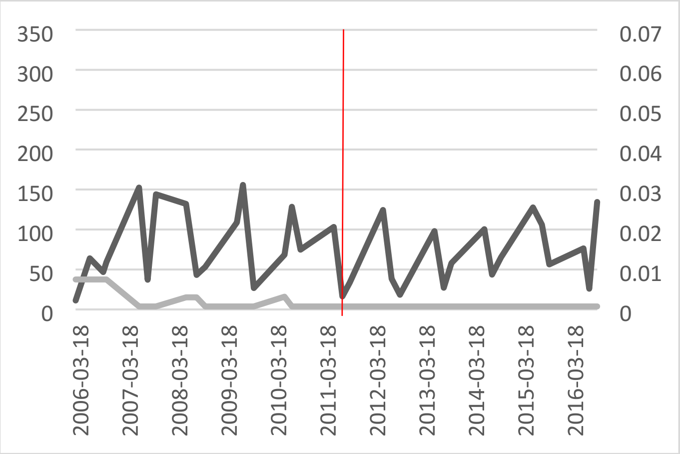
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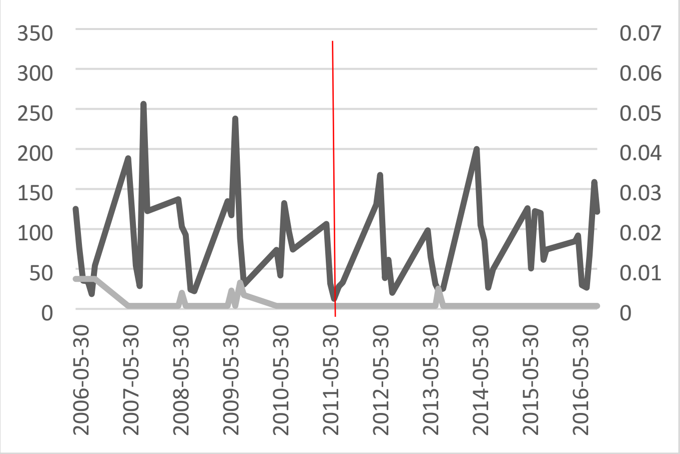
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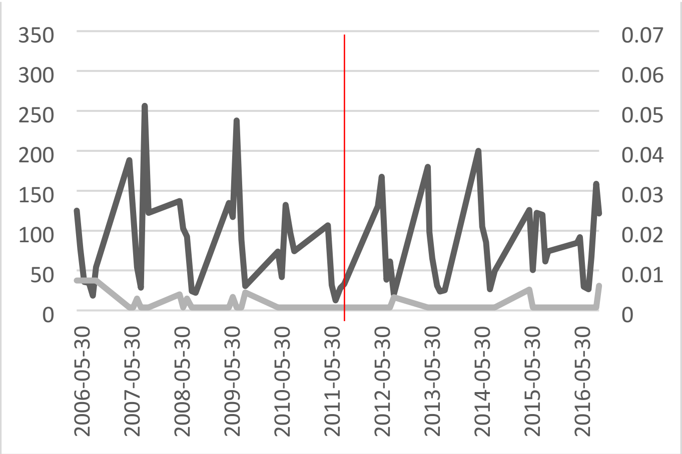
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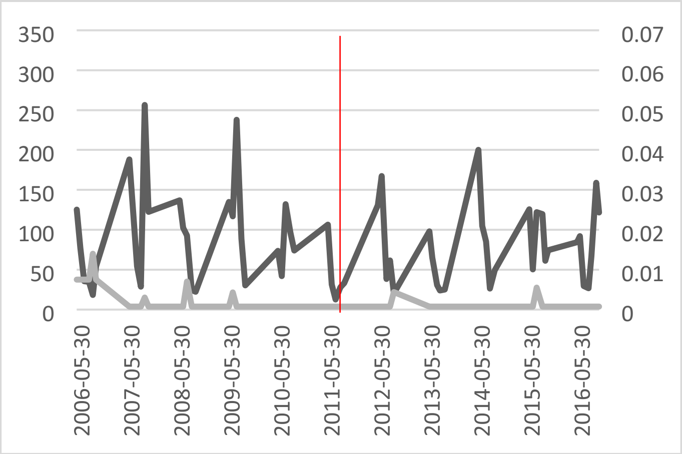
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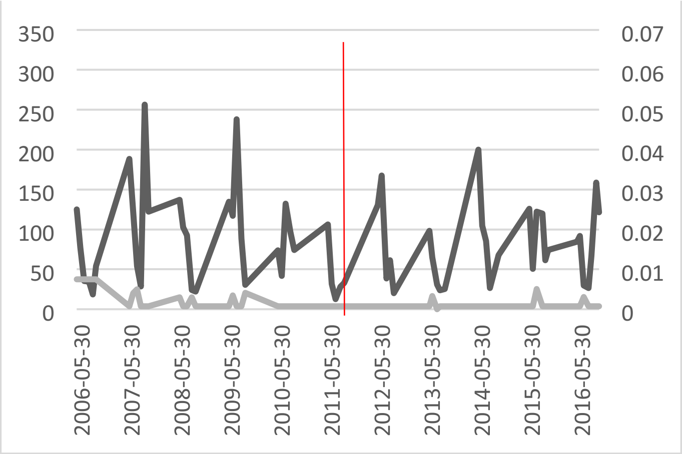
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0
2006-05-30
2007-05-30
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