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Flood Impacts on Dairy Farms in the Bay of Plenty Region, New Zealand

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Abstract: Flood damage assessments provide critical information for flood hazard mitigation under changing climate conditions. Recent efforts to improve and systemise damage assessments have focused primarily on urban environments with few examples for primary industries such as dairy. This paper explores the adverse consequences of flooding on dairy farms in the Bay of Plenty region, New Zealand. Ex-tropical Cyclone Debbie in April 2017 caused prolonged riverine and surface water flooding on over 3500 hectares of dairy farmland. The event provided an opportunity to develop and apply a participatory approach for collecting information about on-farm flood damage, and both response and recovery actions implemented by dairy farmers. Semi-structured interviews and transect walks with farmers revealed a range of direct and indirect damages to production and capital assets, influenced by duration of inundation, silt deposition and seasonality. Results highlight the need to identify on-farm and off-farm asset interdependencies of dairy farm systems to estimate long-term socio-economic consequences at farm-level. Enhancing dairy farm flood resilience in a changing climate will rely on farm-level response and recovery plans, proactively supported by emergency management agencies, farm service suppliers and support agencies.

Keywords: agriculture; dairy farm; flooding; damage; production and capital assets; New Zealand

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1. Introduction

Complex hazard events such as floods cause considerable damage to climate-sensitive, resource-dependent industries and their connected communities [1–3]. In order to reduce vulnerability to changing flood hazards and risks due to climate change, adaptation will be required [4–6]. Decision makers implementing adaptation actions must understand industries' vulnerability to adverse consequences in terms of who is vulnerable, the nature of the vulnerability, the nature of the stresses, and the capacity to adapt to ongoing changing risk where uncertainties prevail [7–11]. This can be informed by systematic and holistic damage and risk assessments, promoted in the Sendai Framework for Disaster Risk Reduction which calls for greater understanding of disaster risk in all its dimensions, and strongly advocates for local and central governments and other stakeholders to undertake this type of assessment [12,13]. Although damage and risk assessment is fundamental to flood risk management, decision makers face implementation challenges including access to risk data and analytical tools for evidence-based disaster risk reduction activities [14,15].

A significant challenge for adaptation and risk management in the face of growing uncertainty and change is understanding the potential for more intensive widespread cascading impacts of multi-hazard events [16–20]. Climate change acts as a risk multiplier in complex systems, defying easy or definitive resolution [21–23] and, consequently, studies to date have focused on impacts to built assets in urban environments [24]. There is a general assumption that urban environments will sustain higher economic losses than other land use types such as agricultural production. This takes attention from understanding the damage potential to high economic value production land use, and the socio-economic linkages between productive and urban economic activities [25–28]. The linkages between agricultural production and urban economic activities are highly relevant in economies in which the productive industries generate a large proportion of national gross domestic product (GDP) [29]. For example, agricultural sectors in New Zealand (e.g., horticulture, dairy, forestry, etc.) contribute nearly 8% of GDP and account for 79% of export earnings [30]. These sectors also employ over 350,000 people, making them fundamental to the socio-economic wellbeing of primary producers, regions and the communities they support [31]. Production land also performs a significant role in New Zealand's food security, biodiversity and flood hazard management. Despite the importance of agriculture, flood hazard exposure of production (e.g., livestock) and capital (e.g., structures) assets is a regular occurrence, yet the direct and indirect damages and their cascading socio-economic consequences are less frequently examined compared to urban flood damages [32].

The social and economic importance of agricultural production deserves a well-developed understanding of its flood damage potential [26,33]. This is required for effective implementation of flood mitigation measures to reduce impacts on agricultural assets and the communities and economies they support. Previous flood damage studies for agricultural assets are predominantly focused at the macro-scale or/and on crop yield loss with little examination of livestock agriculture at meso- or farm-level using a systems lens, considered vital for adaptation [34,35]. Bremond et al. [31] highlights the need to consider farm-level damage assessments using expert knowledge of flood damage and farmers' post-flood recovery practices. Furthermore, climate hazard risk assessment methods need to consider the farm as a system, intricately connected by both internal and external dependencies [25,36].

To address these gaps, this paper uses a case study analysis to gain insight into flood damage on dairy farms in New Zealand's Bay of Plenty region, following ex-tropical Cyclone Debbie in April 2017. Using post-event interviews and on-farm surveys, we document and provide commentary (1) on-farm flood hazards, (2) production and capital asset damage, and (3) factors influencing on-farm flood recovery. We then discuss implications of the survey findings for dairy farm flood damage assessments to inform response and recovery actions that limit socio-economic consequences on dairy farms from future flooding events.

2. Materials and Methods

2.1. Case Study Location and Extra-Tropical Cyclone Debbie

New Zealand is a small, developed economy, with a maritime, midlatitude climate and is annually exposed to ex-tropical cyclones (ETCs) [37]. Consistent with global trends, New Zealand is already experiencing the effects of climate change including more frequent and intense drought [38,39] and extreme rainfall [40]. These are expected to continue, with adverse impacts for the primary sector [6,41], with significant implications for the nation's dairy industry [42,43].

Regionally and nationally, the dairy industry plays a significant role in economic development. New Zealand's almost 5 million dairy cattle produce 3% of the global milk supply from 1.7 million hectares of land [43,44], and is the world's largest exporter of dairy products. While dairying takes place throughout the country, seventy percent of the nation's dairy herd is based on the North Island.

The case study was conducted in the Bay of Plenty region (BoP) on the east coast of the North Island (Figure 1). Dairy farming here is concentrated on the low-lying fertile floodplains in the east, which were extensively drained at the turn of the 20th century, in order to accommodate expanding and intensifying agricultural production [45]. The climate is subtropical: warm humid summers and mild winters [46]. Precipitation is seasonal, with nearly half the annual rainfall falling between May and August. Inter-annual climate variability is strongly influenced in the short- to medium-term by inter-decadal climatic drivers (e.g., Interdecadal Pacific Oscillation, El Nino–Southern Oscillation) [47].

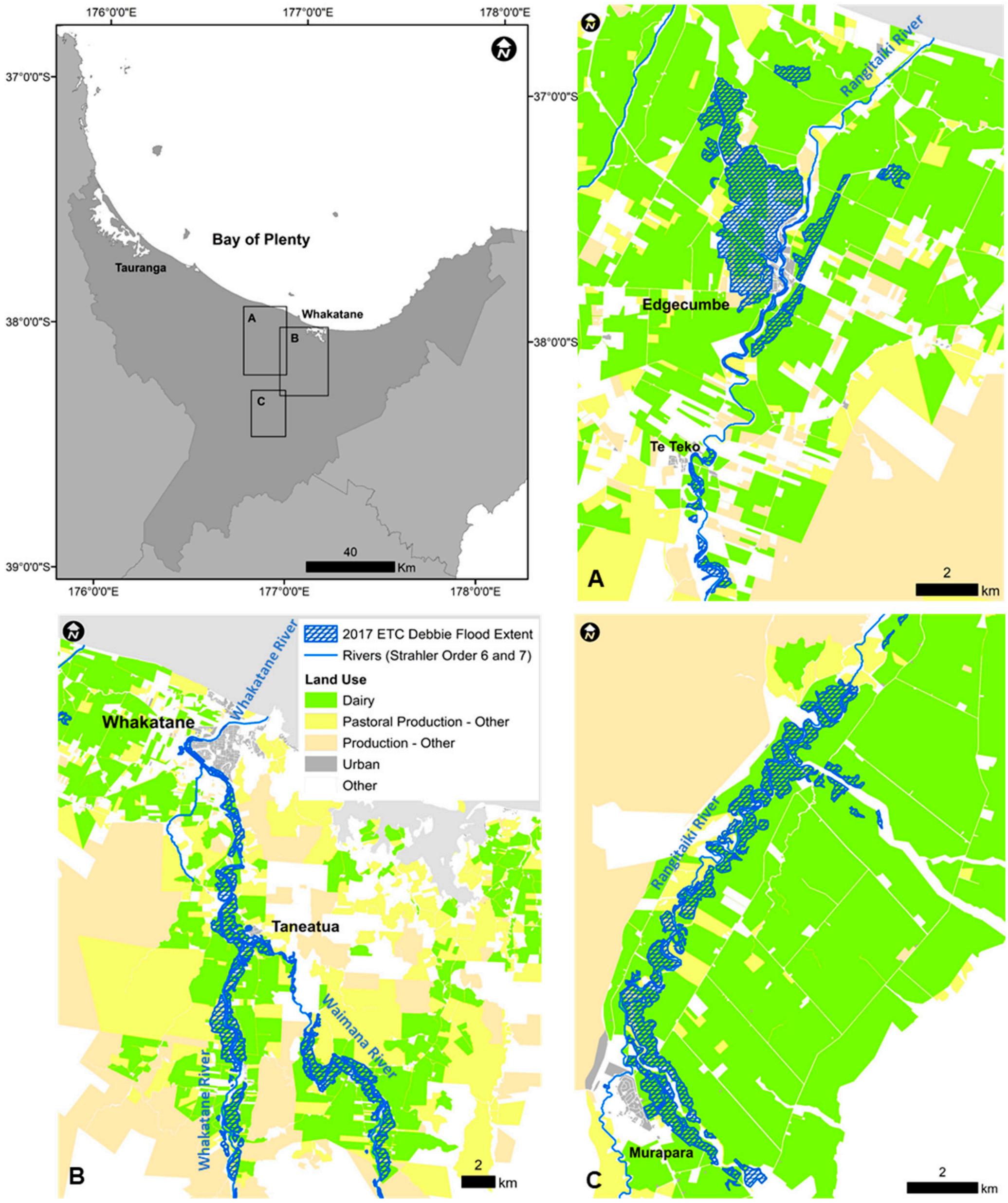

Figure 1. Study area map including approximate flood extents identified from satellite images and dairy farmland use coverage. Case study farms are not identified to preserve the privacy of farmers.

Dairy farms in the BoP region typically manage annual production in line with seasonal conditions [42,48], a reversal of northern hemisphere cycles. In New Zealand, milk production peaks in the spring period between September and November; production continues through the summer months, often with the assistance of supplemental feeds such as maize or palm kernel expeller. In the autumn "dry-off" period, milk production is discontinued, and pasture conserved through reducing stocking rates on farms, including stock unit (i.e., dairy cattle) and transportation to off-farm "run-off blocks" for winter grazing. On-farm stocking rates are returned to normal levels during the August to September calving months. Dairy farm productivity, therefore, is dependent on regular weather patterns and yet climate change is introducing increased climate variability and more frequent intensive extremes [49,50].

In April 2017, two ETCs tracked through the region in short succession. ETC Debbie formed from a tropical cyclone on 29 March 2017, as it migrated toward New Zealand from Queensland, Australia. The ETC stalled over northern NZ after meeting a north-moving frontal system, causing intense and widespread rainfall across the BoP region (Figure 1) between 3 and 5 April. In the Rangitaiki and Whakatane River Catchments, 48 h rainfall totals of 200 mm to 300 mm were recorded, including shorter periods of high intensity rainfall exceeding 30 mm per hour [51]. These conditions were preceded by a "wetter than normal" March, where rainfall totals were 150% to 500% above normal across the BoP region. On Thursday 6 April, stage levels in the Rangitaiki River at Te Teko peaked at 6.5 m (above local datum), leading to a levee failure at Edgecumbe township and the inundation of approximately 5200 hectares of land in the Rangitaiki and Whakatane River catchments.

The Rangitaiki and Whakatane river floodplains are managed by a complex network of levees, flood gates, diversion channels, drains and pump stations that remove excess water from grazing pasture during wetter winter months, and regularly prevents waters from entering farms from neighbouring rivers and streams during flood events. Dairy farming is the prominent floodplain land use in 2016, covering an estimated area of 40,298 ha [52]. Flooding caused by ETC Debbie inundated just over 3500 ha of dairy farmland, with 1858 ha and 1681 ha in the Rangitaiki and Whakatane catchments, respectively (Figure 1). In Rangitaiki catchment, flood inundation was exacerbated in the lower floodplain due to failure of a stopbank (i.e., levee) at the township of Edgecumbe. In the lower Rangitaiki river catchment, the Edgecumbe levee failure exacerbated flooding on dairy farms, causing complete inundation on some properties.

2.2. On-Farm Surveys

There are very few standard methods for post-flood damage assessment data collection. Approaches vary from qualitative expert interviews, direct quantitative measurements and experimental modelling (see [33] for a review of methodologies). To gain insight into the impacts of the flood, interviews and post-event survey were used as the primary methods for data collection. Due to the challenges of access immediately after the flood, the long-term emergent and accumulation of loss as well as important ethical concerns relating to carrying out research during disaster recovery [53–55], a post-event survey was only possible several months after the flood. Drawing on recommendations for best practice [35], the survey was designed to capture farmers' expert knowledge to develop a detailed picture of on-farm events before, during and after the flood event. Survey data were supplemented with semi-structured interviews, with interviewees as experts relaying their experience [56]. Open-ended questions provided guidance without restricting interviewee response. Alongside key informant interviews, field observations were employed with five diverse dairy farms in the BoP region.

On each farm, semi-structured interviews were used to solicit respondents for information on: (1) general description of the flood event; (2) actions taken during and after the flood; (3) estimation of direct and indirect economic losses; (4) production and capital asset damage; (5) challenges for recovery. Following each interview, a farm walk was conducted to observe and record flood damage to production and capital assets [57]. Farm walks were important for observing the remaining damage and acted as a prompt for discussion similar to transect walk methods used within Participatory Rural Appraisal [56,58] and walking interviews. Each farm visit lasted three to four hours.

Deliberate sampling was used to select interviewees operating five flood-affected dairy farms in the Rangitaiki and Whakatane River catchments. Farms were selected due to the flood hazard characteristics experienced on-farms (e.g., inundation area, inundation duration, sediment deposition, erosion) that typically affect dairy farms in the BoP region and other New Zealand regions [59]. Farm geographical spread within catchments and farm legacy (maturity and experience) was also considered during farm selection to ensure dairy farm flood impacts, response and recovery were variable for a relatively small survey sample. Interviewees operating dairy farms were approached through a gatekeeper from Federated Farmers of New Zealand—the national farm advocacy organisation—to host interviews in September 2017, four months after farm exposure to flooding.

Interviews were transcribed and analysed using deductive thematic analysis to identify direct and indirect damage and economic loss, and their influencing factors [60]. This interview analysis approach reveals recurring, but often undocumented themes such as farmer wellbeing, maturity, adaptation methods and support networks used by farm operators to manage on-farm flood impacts.

3. Results

The farm operator interviews revealed three overarching themes presented here in three sections: (1) on-farm flood hazards (Section 3.1); (2) production and capital asset damage (Section 3.2); (3) factors influencing on-farm flood recovery (Section 3.3).

3.1. On-Farm Flood Hazards

Flood waters on surveyed farms covered an area of approximately 740 ha, 20% of flood-affected dairy farm area in the Rangitaiki and Whakatane River catchments (Table 1). In the BoP region, regular seasonal flooding during winter months is anticipated and managed on farms; however, ETC Debbie flooding of grazing pasture in April coincided with the autumn milk production months. The onset and duration of flooding preceded the "normal" operation of dairy herd "dry off" from late May to August.

Table 1. A summary of dairy farm attributes and on-farm flood hazard characteristics.

Farm ID	Farm Size (ha)	Stock Units	Flood Hazard Characteristics				
			Inundation Area (%)	Inundation Duration (days)	Sediment Deposition (mm)	Contamination	Erosion (Pasture)
Rangitaiki 1 (RT1)	210	642	90–100	14	<10	Yes	No
Rangitaiki 2 (RT2)	130	260	30–40	14	<10	No	No
Rangitaiki 3 (RT3)	108	379	40–50	7	10 to 1000	Yes	Yes
Whakatane 1 (WK1)	137	114	30–40	5	10 to 500	No	No
Whakatane 2 (WK2)	154	300	90–100	3	10 to 300	No	No

Dairy farms located along Whakatane River were exposed to flood inundation depths up to 6 m above pastureland. On all farms, operators cited that inundation depths typically averaged 1 m to 1.5 m on their properties. Flow velocities were relatively higher in the upper Whakatane River catchment, causing channel avulsion, pasture erosion and gravel deposition. Flood inundation duration on pasture was longest on farms in the lower Rangitaiki catchment, with some experiencing 14 days of water coverage. Sediment deposition was observed on all farms but ranged from <10 mm to 500 mm on farms in the lower Whakatane River catchment, while up to 1000 mm of sand and gravel was deposited on pasture in the upper catchment. Silt deposits in the lower Rangitaiki catchment were contaminated with sewage, caused by the inundation and failure of upstream urban wastewater oxidation ponds.

3.2. Production and Capital Asset Damage

Dairy farms are complex interdependent systems. An individual farm operates from the interaction of on-farm production (e.g., livestock, pasture, supplementary feed) and capital assets (e.g., buildings and structures (e.g., races and tracks, fences, water and energy) and off-farm support from infrastructure and rural service providers. ETC Debbie direct and indirect flood damages observed or reported for dairy farm production and capital assets (Table 2) are described in Sections 3.2.1 and 3.2.2, and off-farm assets and services identified by farm operators in Section 3.2.3.

Table 2. On-farm production and capital asset categories and types exposure to flooding.

Category	Asset Type	Asset Attributes
Production	Livestock	Dairy cattle
	Pasture	-
	Supplementary feed	Hay bales; baleage (wrapped hay bales); silage
Capital	Buildings	Residential Milking shed Auxiliary (supplementary feed storage; equipment and plant storage; water pump, calf rearing)
	Structures	Races and tracks Fences and gates Water (bores; drains; effluent sumps; pipelines; pumps; tanks; troughs) Energy (utility poles; fuel tanks)

3.2.1. On-Farm Production Assets

Farm operators identified flood damage to production and capital assets at paddock (i.e., field) to farm-levels. Farm-level direct and indirect damage types are summarised in Table 3 along with the estimated financial loss from associated recovery actions in Table 4.

Table 3. A summary of direct and indirect damage type observed and reported on surveyed Bay of Plenty region dairy farms.

Asset Type		Direct	Indirect
Production	Livestock	• Disease/loss of condition (e.g., Mastitis) [RT1] • Removal of livestock from farm [RT1, RT2, RT3, WK1, WK2]	• Off-farm transportation cost [RT1, RT2, RT3, WK1, WK2] • Off-farm grazing costs [RT1, RT2, RT3, WK1, WK2] • Cost of vet services [RT1] • Lost income from drying off cattle early [RT1, RT2, RT3, WK1, WK2] • Lost income from early sale of cattle for slaughter [RT3, WK2] • Disruption to dairy cycle e.g., early drying off [RT1, RT2, RT3, WK1, WK2] • Lower calving due to poor health and stress [RT1, RT2, WK1, WK2]
	Pasture	• Pasture damage and loss [RT1, RT2, RT3, WK1, WK2] • Loss of pasture (e.g., erosion or temporary land use change) [RT3]	• Cost of reseeding and fertilizing damaged pasture [RT1, RT2, RT3, WK1, WK2] • Cost of off-farm grazing due to silt cover or water damage [RT1, RT2, RT3, WK1, WK2] • Cost of silt and debris removal [RT3, WK1, WK2]

Table 3. *Cont.*

Asset Type		Direct	Indirect
	Supplementary feed	• Crop (e.g., maize) damage and loss RT1 • Baleage and silage damaged or washed away RT1, RT2, WK1, WK2	• Cost to replace damaged or washed away baleage and silage RT1, RT2, WK1, WK2
Capital	Buildings	• Damage to dairy shed equipment, feed storage sheds RT1, RT2, WK2	• Cost to repair or replace dairy shed equipment, feed storage sheds RT1, RT2, WK2 • Loss of income for seasonal workers RT1, RT3
	Structures	• Damage fences, gates, drains, races and tracks, water troughs RT1, RT2, RT3, WK1, WK2	• Cost to repair or replacement RT1, RT2, RT3, WK1, WK2 • Cost of contractor services RT1, RT3, WK1 • Cost of reseeding by helicopter due to limited access to paddocks reseeding RT1 • Cost of silt and debris removal RT3, WK1, WK2

Table 4. A summary of flood hazard exposure and damage response and recovery actions with associated farm-level economic loss time estimates reported as an addition to "normal operating" activities on surveyed Bay of Plenty region dairy farms.

Asset Type	Production or Capital Asset Response or Recovery Action		Farm-Level Economic Loss (NZD 2017)	Response or Recovery Time
Production	Pasture	Sediment and debris clean-up RT3, WK1, WK2	2000 to 8000	2–3 months
		Re-grassing (seed, fertiliser, spreading, weed spraying) RT1, RT2, RT3, WK1, WK2	10,000–170,000	4–6 months
	Livestock	Veterinary services RT1	<12,800	0–6 months
		Stock transport RT1, RT2, RT3, WK1, WK2	6000–60,000	2 days–1 week
	Supplementary feed	Off-farm grazing RT1, RT2, RT3, WK1, WK2	9000–112,000	4–5 months
		Purchased feed RT1, RT2, WK1, WK2	6000–217,000	2–3 months
Capital	Milking shed plant/equipment repair and replacement RT1, WK2		100,000–150,000	2–3 months
	Fence cleaning and repair RT1, RT2, RT3, WK1, WK2		2000–5000	2–3 months
	Farm race and track cleaning and repair RT1, RT2, RT3, WK1, WK2		5000–140,000	3–4 months
	Water trough cleaning and repair RT1, RT2, RT3, WK1, WK2		1000–5000	2 weeks–1 month
	Drain cleaning and repair RT1, RT2		Up to 10,080	3–5 months

Production asset damage was mostly incurred to pasture and supplementary feed. Pasture die off occurred when flood inundation duration exceeded five days or on farms where sediment deposition exceeded 100 mm. Prolonged wetting of soil and sediment deposition also prevented tractor access, delaying entry by several months further prolonging rehabilitation of pasture. Prevention of sediment removal and pasture reseeding was expected to delay the use of paddocks by 6 to 12 months. Some farmers were able to reseed pastures prior to winter months using helicopters for aerial seed broadcasting; however, this was expensive, costing NZD 1900 per 1.5 h of helicopter hire, in addition to seed and fertiliser purchase (up to NZD 3000/ha). Farmers who did use this method said it would still take at least 3–4 months for pasture to be usable for grazing.

In addition to pasture damage, supplementary feed stored on-farm for grazing during winter months was also exposed to flood waters. Feed is typically stored as either plastic wrapped hay bales or silage stacks, and when wetted, became rotten and unusable for stock feed within a week of flood exposure. Although some farmers used affected feed to grazing stock remaining on-farm during the week after flood waters receded, most was discarded incurring additional costs for production or feed purchase. Feed stores were not replaced for winter grazing due to farm recovery and low stocking rates, which reduced some potential feed recovery costs for farmers.

Maize crops grown on-farms were destroyed, and prolonged soil saturation of both on-farm and off-farm cropping paddocks caused abandonment of maize planting during autumn months. In both cases, direct crop losses and delayed planting would disrupt normal crop cycles for up to several years. Maize crop replanting or planting later than normal would lead to delayed harvests of crops the farm operators rely on for feed or supplementary income.

Farmers observed no livestock mortality from direct exposure to flood waters. This was primarily due to evacuation to higher ground or holding areas (i.e., stand-off pads) before and during the flood. After flooding, half the farms reported up to 10% of cattle contracting mastitis, a potentially fatal inflammatory reaction of the udder tissue that contributed to the need to "dry-off" over one month earlier than normal. Persistent soil saturation following ETC Debbie during subsequent winter months meant that mastitis continued to cause health issues for cattle remaining on farms, reducing their condition going into calving and lactation during spring months.

During winter months livestock transport off-farms is a widespread practice, as cattle are "dried-off" and stocking rates are reduced to limit pasture and soil damage. The impact of ETC Debbie, however, required farm operators to implement this practice one to two months earlier than normal, in the autumn. The "wetter than normal" conditions in the BoP region required transportation of livestock onto farms in neighbouring regions (e.g., Waikato and Hawkes Bay) for winter grazing. One farmer estimated an average transportation cost of NZD 110 and NZD 25 per stock unit (i.e., dairy cattle) for off-farm grazing. Most farmers interviewed were able to transport livestock off-farm during the first 48 h of ETC Debbie, as pastures began to flood. However, higher than normal numbers of off-farm transport and grazing of livestock, longer transport distances and a longer off-farm grazing period doubled the operation costs on some farms for this practice relative to normal operating conditions.

3.2.2. On-Farm Capital Assets

Milking sheds are the most important capital asset on dairy farms. On surveyed farms, the cattle were milked twice daily using herringbone systems, with milk stored in vats for transfer into tanker trucks and transport to processing plants. Two milking sheds on Rangitaiki 1 (RT1) and Whakatane 2 (WK2) were inundated by flood waters of 0.8 m and 1.5 m, respectively. Minimal flood damage to RT1 milking shed components was sustained at the lower flood depth as in this instance, electrical services, computer equipment, condenser units and milk storage vats were located above flood levels. Shed construction frames, external walls, floors, holding pads and milking equipment are hosed down twice a day following milking sessions; therefore, most building components resist water damage. At the higher flood depth on WK2, water caused damage to electrical switch boards and fittings, condenser units, computers and storage vats. These components were located lower to the ground and silt carried by flood waters was deposited on suction cups and inside milk storage vats, water and feed troughs, requiring cleaning and sterilisation before reusing when repaired. If left uncleaned and sterilised, milk produced in the shed would be rejected for pick up and processing by milk companies.

Other auxiliary buildings and structures (e.g., fences, races and tracks) on farms sustained "minor" repairable direct damage. Even repairable damage incurred financial losses for farmer and service contractor labour and equipment use. For instance, on RT1 and RT3 flood-affected track and race repairs alone cost approximately NZD 5000 to NZD 15,000 per kilometre. Debris on permanent fences was removed by hand to prevent electrical shorting. The farm operator of WK2 reported that 15 contractors and volunteers required two weeks to clean fences and repair damage. On farms affected by sediment deposition (e.g., WK1 and WK2), partially or fully buried structures such as fences and water troughs were dug-out or lifted to the new floodplain level. This process was delayed by 6 to 8 months for some paddocks due to prolonged saturation of soil and deposited sediments prohibiting tractor access.

Water supply components, including troughs, pipelines and tanks sustained no or minor replaceable damage despite exposure to flood waters exceeding 4 m in some cases. Flood exposed stock drinking water troughs required cleaning on all farms due to sediment deposition and sewage contamination on RT1. Water drainage components, such as drains and pumps, were blocked from sediment and debris deposition, rendering them ineffective (RT1). Sediment deposition in drains exacerbates both soil saturation over winter and spring months and the risk of future flooding. Farm operators on RT1 and RT2 cited that, at farm-level, open drains requiring dredging would take several weeks to complete.

3.2.3. Off-Farm Infrastructure Assets and Support Services

Farmers also described the significance of lifeline infrastructure and rural support services during flood event response and recovery. Farmers on RT1, RT2 and WK2 noted that although electricity services were not damaged or disrupted during and after the event, access to farms from the local road network was disrupted. These farmers evacuated their properties but were able to move stock to higher ground on-farms prior to flood inundation due to early warnings ranging from hours to days. However, farmers could not access properties for several days due to flood waters preventing vehicle use of roads and emergency cordons limiting access on inundated land to search and rescue first responders. The inability to access properties to milk cattle for up to a week, resulted in lost income from reduced milk production and forced early dry-off but caused animal health issues, including increased incidents of mastitis and reduced animal condition, leading into winter months.

Rural services and suppliers (e.g., veterinary services, cattle transport, equipment and plant, seeds, fertiliser, earthworks, etc.) remained in operation and accessible to farmers during and after the flood event. Farmers stated cattle transport off-farm and onto safe pastures was the most immediate need for managing stock welfare and production losses. Transport operators increased these services in response to demand during and after flooding. Similarly, rural suppliers offer services to farmers outside of normal operating conditions (e.g., weekends and public holidays) to support recovery efforts. Farmers noted the importance of established relationships with rural contractors and suppliers is critical for delivery of timely services and access to resources to support on-farm recovery.

3.3. Factors Influencing On-Farm Flood Recovery

Farmers interviewed commonly cited seasonality, farm access, farm legacy (maturity and experience) and farmer wellbeing as key factors influencing farm recovery to "normal" operating activities.

3.3.1. Seasonality

Dairy farm production activities in the BoP region vary during the year to coincide with seasonal weather patterns (Figure 2). Managing farm activities around flood hazards is a normal part operating on the Rangitaiki and Whakatane River floodplains. In this case, on-farm flooding occurred in early April 2017, near the end of normal sprint to autumn milking months (i.e., September to June). Peak milk production on farms generally occurs in spring months from October to November during the normal period of high yielding pasture growth. Milking may continue during May with favourable climatic conditions, otherwise cattle begin to be "dried off" for the winter months (May/June to August/September). During winter and prolonged wet periods, areas on farms are restricted from grazing to reduce pasture damage and soil loss from cattle. During wet periods, a proportion of dairy cattle are transported to "runoff blocks" (i.e., drier pastureland for winter grazing) for winter grazing. Supplementary feed is usually purchased during to top up the energy requirements of dairy cattle remaining on-farm. This is in addition to feed produced during spring and autumn months when extra pasture or crops (e.g., maize) is grown.

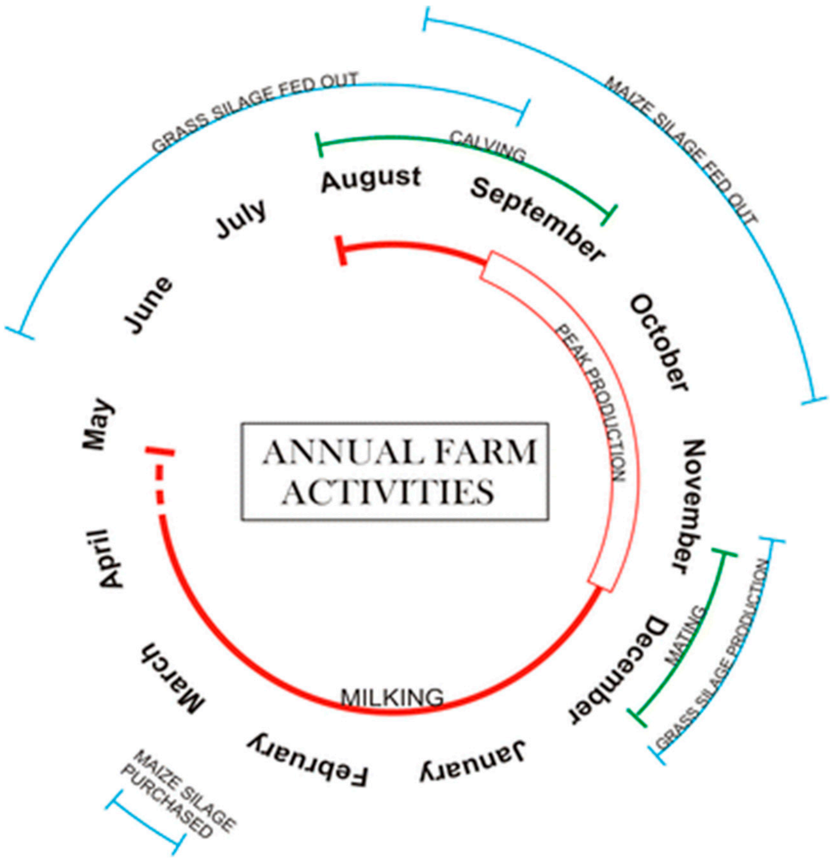

Figure 2. Annual dairy farm activities in Bay of Plenty region showing key vulnerable periods during the year of farming operations [46]. A dairy farm's most important activities are closest to the centre, with activities of decreasing importance progressing further from the centre.

Brémond et al. [35] highlighted through their review that seasonality and duration were the most influential parameters for agricultural flood damage and loss. ETC flooding in April 2017 proceeded a period of wetter than normal soil conditions and was followed by further prolonged wetting of soils and pasture during winter months. Although dairy cattle are normally "dried off" during winter months, cattle on flood-affected farms were dried off and on-farm "stocking rates" reduced prior to winter and remained low into spring months as soils and pasture had not recovered to support grazing. Farmers cited that low stocking rates and reduced milk production during spring months was expected to reduce 2017 annual farm incomes by 20% to 30% and could continue to cause lower than anticipated incomes for two to three years as farms recover.

Temporal periods when pasture growth, quality and access are vital to maintain milk production are demonstrated in Figure 2. Farmers reported that a higher-than-normal proportion of dairy cattle returned from winter grazing in poor health. In general, the longer cattle are "off-farm", and the "wetter" the winter conditions are the more likely cattle health and condition decline. This results in a longer reconditioning time and to return cattle to milk production. On all surveyed farms, ETC flooding occurred a few weeks earlier than planned off-farm stock movement, and drying-off, but a large-scale evacuation of livestock was implemented for those who needed it. The flood event timing and long duration of soil water logging on farms meant dairy cattle were off farm for several months longer than expected in many cases. These factors combined with reduced dairy cattle health and conditioning caused considerable disruption to normal annual dairy farm operations. Farmers estimated the recovery of production assets (i.e., pasture and livestock) could take farms up to three years to return to pre-ETC flood milk productivity. Farm systems, including management practices, are based on long-term, mean climatic conditions. The surveyed dairy farmers require a 2- to 3-year window to recover from extreme events such as ETC Debbie. Increasing climate variability and change has the potential to confound recovery by narrowing the opportunities for recouping financial losses and rebuilding or replacing infrastructure, eroding adaptive capacity [6,28,61–63].

3.3.2. Farm Access

Flood-deposited sediment and debris on farms prevented paddock access and grazing use. On surveyed farms, milk production recovery times were prolonged due to the lack of access to grazing pasture. Pasture remediation after flooding was made difficult from races and tracks requiring sediment clearing and damage repair, and prolonged wet conditions restricting heavy vehicle access. On some farms (e.g., RT1, WK1) paddocks were accessed using helicopters to resow, fertilise and weed spray recovering pasture, while on others (e.g., RT3) access to some paddocks was not possible until the summer months.

Localised flooding of transport networks prevented some evacuated farmers to return to inundated farms an administer animal welfare. Farmers cited that road access to farms was prohibited from a combination of flood waters and emergency management cordons. Cordons were set up in some flood-affected areas on the Rangikaitki River floodplain to manage property access by first responders. Farmers who could not access flood-affected farms noted that animal welfare is a major concern during milk production as dairy cattle that are not milked regularly have a heightened risk of contracting mastitis. This was a concern for farmers on the flat, low-lying farms lower Rangikaitki River floodplain who were unable to move stock to higher ground.

Farmer inability to evacuate or provide welfare for dairy cattle led to considerable stress and tension with emergency service agencies and first responders. According to operators interviewed, no consultation with dairy farmers in the broader community was conducted before road closures prohibited farm access. Farm operators understood the public safety requirements for restricting public access to inundated land but felt there was little or no consideration of emergency response requirements for flood-affected farms.

> *"we would like a more collaborative approach with CDEM when responding to future flood events [Civil Defense and Emergency Management]"*
>
> Farm operator RT2

3.3.3. Farm Legacy

The interviewed farmers provided a depth of understanding of the factors exacerbating socio-economic recovery of dairy farms. Farm experience and ownership were identified as key factors influencing a farmer's wellbeing and financial capacity response and recovery from flood damage. There was no standard practice for asset remediation implemented on surveyed farms; however, mature farmers with >10 years' experience had greater access to financial capital to resource short and long-term recovery actions. These farmers had previous experience of flood damage that informed staging the implementation of on-farm recovery. For example, some farmers resowed pasture immediately and grazed dairy cattle off-farm for 4 to 5 months following the flood, whilst others were more cautious waiting for the threat of repeated flood events to pass altogether but allowing stock to access onto affected paddocks and aerate silt deposits supporting resown pasture.

> *"Some farmers rush into fix things without realising that a second flood may well follow quickly. It is better to wait out the wet season before reseeding"*
>
> Farm operator, WK1

According to interviewees, an ability to make decisions and implement recovery actions varied considerably due to the farm legacy, or experience of the farmer. Interviewees noted repeatedly that different decisions made by farmers would lead to different recovery times and economic losses. Farmers deemed as more experienced, made decisions requiring considerable financial investment immediately after the flood, and they were able to recover quicker in the long term. Farmers that did not have the financial capital to invest in recovery actions immediately, were potentially at greater risk of economic losses and poor wellbeing.

> *"You can't skimp, you have to throw money at it (the recovery)"*
>
> Farm operator, RT1

Interviewed farmers noted that the capacity to make decisions on recovery actions often came from past-flood experience and ability to manage a multi-year farm recovery. Inexperienced farmers cited that they struggled to make effective recovery decisions immediately after the flood, which was likely to cause a longer recovery time to "normal farm operations". This situation occurred on smaller-sized farms that were operated by farmers with <10 years' experience, less access to financial capital or savings and/or were less well connected or supported within agricultural community.

> *"Those farmers without experience or access to financial capital really struggled to make decisions"*
>
> Farm operator, RT2

Experience with managing climate variability is widely accepted as a critical component of adaptive capacity [64]. Climate change, however, presents novel risks as weather patterns and extreme events may have no contemporary analogue or be beyond the collective memory of the region, overwhelming conventional risk management strategies [65]. Local knowledge and experience has a clear role to play in climate change adaptation; however, there are concerns that this is limited as communities face unfamiliar climate patterns, and experience with past climate provides only limited insight for the future [56,66].

3.3.4. Farmer Wellbeing

Farmers reported a range of welfare concerns for either themselves or the broader farming community following the flood event. Their ability to manage mental health and wellbeing after the shock of on-farm asset damage and implement recovery actions was influenced by previous flood damage experience and financial resources. Farmers with >10 years farm ownership all experienced multiple damaging flood events and implemented their farm-level response and recovery based on actions that reduced farm operation disruption from previous events.

Interviewed farmers offered help to neighbouring dairy farmers, and in some extreme cases volunteered their time for several weeks at the detriment of their own farms. The RT2 farm respondent volunteered for 11 days on other dairy farmers to assist with clean-up and recovery activities. However, like all farmers interviewed they cited suffering from mental health issues and required three weeks off their farm during the flood recovery period to help alleviate stress caused by the event. Another farmer (WK1) was unsure they would continue to farm given the stress the flood event had caused to themselves and their family. The mental health implications for farmers caused by flood damage was often detrimental for staging effective recovery actions that reduce economic losses from disrupted dairy farm operation.

4. Discussion

Dairy farms are complex systems comprised of interactions and linkages between production and capital assets within the farm gate [42,43]. Individually and collectively, farms are also connected to larger systems of networked infrastructure such as roads and electricity, product processing and distribution channels [67,68]. Interviews of ETC Debbie flood-affected dairy farm operators in the BoP region highlight the complex interactions of flood impacts with response and recovery activities. Here, we discuss implications for future dairy farm flood damage assessments and mitigation strategies in light of farm operator experiences during and after ETC Debbie flooding.

Dairy farm flood impact investigations have previously focused on quantifying direct damages such as pasture loss and economic consequences from lower on-farm milk production, e.g., [69]. On-farm flood damages are both direct and indirect, with the latter occurring over a prolonged temporal period after a flood event [24]. Interviewed farmers cited the true economic costs for their dairy farms' return to "normal" operating conditions may only be known two to three years after a significant flood event. Over this period, weather and seasonal influences on farm operations and flood recovery action outcomes on milk production combine to determine longer-term socio-economic consequences at farm-level. This implicates risk assessments when either vulnerability models of direct production and capital asset damage are applied to estimate economic loss or informed by post-event empirical damage data for a single point in time, or short duration of post-flood farm recovery [35]. On-farm damage information collection to inform future risk assessments requires consideration of the temporal period spanning from pre-flood preparedness to post-flood recovery extending multiple years after the event. These temporal periods represent both the actions to reduce on-farm direct and indirect damage, and disruption to dairy farm activities, particularly vulnerable periods such as calving and supplementary feed production.

On-farm damage assessments require a temporal appreciation of dairy farm activities to inform future flood risk management [35]. Damage data collection too soon can omit economic costs of long-term production asset recovery, whilst delayed collection means farm operators' recovery progress and cost of indirect damages may not be quantified. On-farm empirical flood damage assessments should align with annual dairy farm activities and planned in coordination with farmers and stakeholders before and after flood events. Information on farm conditions and strategies to reduce production and capital asset damage should be collected pre-flood event. Post-event direct and indirect damage assessments should occur as soon as ethically appropriate following the event (e.g., 3 months), then again at set intervals (e.g., 6 months, 1 year, 2 years, etc.). This will determine the influence of farm conditions and mitigation strategies for reducing direct or indirect damage, and implications for farm-level economic losses incurred farms as operators implement recovery during annual dairy farm activities. Understanding the factors influencing economic loss or hindering recovery of dairy farm activities can inform contingency plans for emergency managers, farm service and support agencies to support on-farm recovery activities, thereby limiting socio-economic impacts.

Interdependencies between on-farm production and capital assets, and off-farm services and support networks, create a highly complex system that maintains dairy farm operation. In BoP region, we observed that flood-affected farms comprise elements that form a network of interdependencies. For instance, milking shed operation for milk production and distribution is dependent on and off-farm electricity distribution and vehicle (i.e., milk tanker) access using on-farm tracks and off-farm road networks. Here, the interdependency between milk production and infrastructure network services meant flood disrupted farm electricity supply and transport access reduced milk production over the short-term (days–weeks) due to inoperable milking sheds and medium term (months) due to earlier than normal dairy cattle "dry-off" prior to winter. Recovery to "normal" milk production levels was dependent on the ability of farm operators to restore pasture and on-farm capital assets (e.g., races, tracks, fences, water supply and treatment structures). This was dependent on farm operator ability access and finance labour and resources from farm service suppliers. Milk production during post-flood recovery was further dependent on operators to restore production and capital assets to meet prescribed environmental standards (e.g., the "Dairying and Clean Streams Accord") before milk purchase and distribution services resumed. These interdependencies for on-farm milk production suggest future flood damage and risk assessments determine the network of interdependencies between on-farm production and capital assets and off-farm services during annual dairy farm activity periods.

Dairy farm capacity to mitigate flood damage relies on farm-level response and recovery plans, proactively supported by emergency management agencies, farm service suppliers and support agencies. BoP dairy farmers stated cattle transport off farm and onto safe pastures was the most immediate need for managing cattle welfare and production losses. Implementing such response actions requires collaboration with emergency management agencies to ensure timely off-farm evacuation of dairy cattle and their on-farm welfare can be conducted safely. Future response actions could be supported by catchment models for flood forecasting, either deterministic or data driven, that provide early warnings and critical information for implementing off-farm cattle evacuation prior to on-farm flooding [70]. Effective on-farm response informed by early warnings would be dependent on the relationships of farmers with service suppliers and support agencies. BoP dairy farmers also relied on established networks with farm service suppliers (e.g., cattle transport, veterinary service), often more difficult to access by farmers with <10 years' experience, leading to adverse socio-economic consequences due to reduce on-farm cattle welfare and milk production. Determining such dependencies, their potential socio-economic impacts during a return to "normal" dairy farm operation is essential for future farm-level flood damage assessments that inform multi-stakeholder response and recovery plans.

Traditional deterministic or probabilistic flood risk models that determine a likelihood of socio-economic consequences for elements exposed to hazard intensities are applicable for determining direct damage to dairy farm production and capital assets [24,35]. These models can simplify the complex interdependencies between on-farm assets and off-farm infrastructure and services that support dairy farm operations. Determining system interdependencies has become a recent focus for dairy farm damage assessment and evacuation modelling for the management of cattle welfare for locations exposed to volcanic hazards [71]. Future quantitative system interdependency model development would provide powerful tools for flood damage assessments that support evidence-based mitigation strategies for dairy farms, along with the communities and economies they support.

5. Conclusions

This study presents the adverse consequences of flooding on dairy farms in the Bay of Plenty region, New Zealand. We conducted on-farm semi-structured interviews with farmers whose dairy farms were exposed to riverine and surface water flooding from ETC Debbie in April 2017. The interviews revealed detailed information about on-farm flood hazards, production and capital asset flood damage, and factors influencing on-farm flood recovery.

Flood-affected dairy farms sustained a range of direct and indirect damages, disrupting normal operating activities. Direct damage to production and capital was attributed to flood duration and silt deposition, while indirect damage, causing economic loss and impacts on farmer wellbeing, was influenced by seasonality and the recovery and response actions implemented at farm-level. Farm maturity, including duration of ownership and financial resources, contributed to the socio-economic outcomes of dairy farm recovery. Furthermore, limiting economic losses required access to transport and electricity; hence, infrastructure network services were critical for dairy cattle evacuation and welfare during and after farm inundation.

The observations presented here highlight a future research requirement that extends beyond quantification of direct damages to on-farm assets. While this remains highly important for dairy farm flood damage assessments, research effort focused on indirect damages occurring over temporal periods associated with annual dairy farm activities and analysis on-farm and off-farm asset interdependencies of dairy farm systems will enable long-term socio-economic consequences to be quantified at farm-level. Determining system interdependencies and their influence on socio-economic impacts during a return to normal dairy farm operations is essential for future flood damage assessments that inform multi-stakeholder response and recovery plans.

Interdependent on-farm production and capital assets, and off-farm services and support networks create a highly complex system that maintains dairy farm operation. Future dairy farm flood damage assessments and models should consider system interdependencies to quantify the disruption to normal farm operations and effectiveness of potential on-farm and off-farm response and recovery actions for reducing socio-economic consequences. System interdependency models would provide powerful tools to deliver evidence-based mitigation strategies for dairy farms, along with the communities and economies they support to ensure long-term sustainability and resilience in response to future climate change.

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