# Journal of Geographical Research

BILINGUAL PUBLISHING CO.
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Volume 4 • Issue 3 • July 2021
ISSN 2630-5070(Online)

Volume 4 Issue 3 • July 2021 • ISSN 2630-5070 (Online)

# Journal of Geographical Research

**Editor-in-Chief**

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Volume 4 | Issue 3 | July 2021 | Page1-60
Journal of Geographical Research

# Contents

## ARTICLE



## REVIEW

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**Journal of Geographical Research**
https://ojs.bilpublishing.com/index.php/jgr

ARTICLE

# Innovative Practices for the Promotion of Local/Indigenous Knowledge for Disaster Risk Reduction Management in Sudur Paschim Province, Nepal

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ARTICLE INFO

*Article history*
Received: 14 May 2021
Accepted: 31 May 2021
Published Online: 3 June 2021

*Keywords*:
Multihazard
Indigenous knowledge
Location-specific
Innovative practice
Indigenous communities
Science to policy

ABSTRACT

This study is an attempt to point out the different types of natural hazards in Sudur Paschim province of Nepal where environmental degradation processes such as deforestation, desertification, biodiversity loss, soil crisp and watershed degradation are rising trends. Using participatory method multi hazard prone areas were identified with type and intensity. Multi criteria evaluation method was applied to prioritize replicable actions with location-specific innovative practices and their legitimization for integrating local and indigenous knowledge into mainstream education, science and policy with a view to incorporate local and indigenous knowledge as live science in disaster and climate change education. Findings of the study reveal that varieties of natural hazards in combination with social factors such as poverty, conflict and inequality have resulted frequent disasters and social vulnerabilities in many parts of the province. Traditionally, indigenous and local people have responded threats of multi hazards by using their traditional knowledge and skills which has evolved over generations, and continue to adapt to future changes. These traditional, often faith-based, beliefs and practices were found to use as the key to their resilience in the face of natural hazards. However, many communities have been lost their knowledge as the elderly die without transferring it to younger members. Behind this proper educational policy and strategic development plans have not been implemented to cope local/indigenous knowledge into practices. Findings of the study indicate that indigenous and local knowledge is a precious province resource that can support the process of disaster prevention, preparedness and response in cost-effective disaster risk reduction. Therefore, policy framework has to prime focus to integrate indigenous and local knowledge, wisdom and skills into mainstream educational programs in order to transfer science into policy and education (words) into practice.

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*@This paper has been presented at ICDP International Conference, DU-Delhi-16-18 April, 2021*

 DOI: https://doi.org/10.30564/jgr.v4i3.3223

## 1. Introduction

With more frequent and more intense disasters, disaster risk reduction (DRR) has become increasingly important as a fundamental approach to sustainable development. Indigenous communities have traditionally practiced their unique, innovative and location -specific novel activities for resource conservation, utilization and mitigation measures for disaster management. The practices of indigenous communities have widely used as local and location specific knowledge and wisdom in many areas of Hind Kush Himalaya like as the study area [1,2]. By adopting use-oriented approach to traditional knowledge and learning, indigenous knowledge has been considered as value of locals precisely and it has constantly tested and updated over time in spatial perspectives [3]. In this context local and indigenous knowledge system (INKS) holds a unique position in DRR discourse in often more vulnerable than non-indigenous groups and yet also hold location specific practices that enable a greater understanding of hazards and disasters. LINKS is in the wider debates on disaster policies, science and education as well as development agendas and singles to adopt DRR strategies through respect for local and indigenous approaches in coordinating alliances, culturally appropriate incentives, accurate, appropriate, and ethical data base, acknowledgment of local and indigenous land use practices; use of indigenous language, leadership, and institutions, collaboration with indigenous knowledge, and acceptance of traditional approaches [4,5]. The ability a community has to prepare itself for disaster preparedness and risk management needs to be understood within the broader context of livelihood security, sustainability and building up community resilience in the long term [6].

The disaster management methods and practices have to link between local wisdom and scientific principles, strategies, and approaches and institutions such as conventions, government policies, strategies, rules and regulations that altogether govern interaction and integration with community building resilience and sustainable livelihood supporting ecosystems. It is, therefore, integration of indigenous and local knowledge system into disaster management methods and practices is a process of blending these knowledge systems into a rational decision-making, sharing of information and understanding of different viewpoints between the indigenous people and the western trained professionals [7,8]. Disaster management as being a mutual take and give back to nature for the benefit of all components of the supporting socio-economic system and ecosystem such duty is for each of the creation from the communities to the powerful political organization and the spirits [9,10,11].

The adopted Sendai Framework for Disaster Risk Reduction 2015-2030 also addresses knowledge-related issues and provides the opportunity to highlight the critical role of knowledge in disaster risk reduction. The framework encourages investment in innovation and technology development in disaster risk management. However, needs for science and technology inputs are unmet, and there is a lack of policy making that is based on science and evidence due to the issues like networking, coproduction of knowledge, and a stronger role played by academia searching innovative approaches and tools that could play game change role for DRR.

Local and indigenous knowledge needs to be integrated with science before it can be used in policies, education, and actions related to disaster risk reduction and climate change. Integration of local and indigenous knowledge to natural hazards and climate change with science can be developed through the process of observation, documentation, validation, and categorization of local and indigenous knowledge with a view to identify knowledge that can be integrated with science, which could then be further disseminated for use by scientists, practitioners and policy-makers, and safeguard and valorize those that cannot be scientifically explained in order to promote the use of local and indigenous knowledge to enable communities to increase their resilience against the impacts of climate change and disasters [12]. Thus, education has to be taken as an important component of disaster management for introducing disaster preparedness, prevention and response and information on predicting, preparing for, and responding to hazards have to be introduced in the curricula of schools and universities [13].

This paper tries to find out the best mitigation solution through study of past disasters in West Seti and Thuli gad watersheds and, effect of construction works in Siwalik foothills disasters such as landslides, soil erosion and drying of water sources in upstream and flash flood and river bank cutting in downstream of watersheds. Attempting main focus of the study, the paper further reflects the collective understanding and aspirations of people in the West Seti and Thuli gad watersheds so they can provide baseline information to help to identify hazard prone areas, mitigation measures and priorities for livelihoods improvements and supports the development of tools for watershed planning and approaches for collaborative management for the safer lives and better outcomes of the watersheds. Using political -ecological approach in the sense of citizen science, the main thrust of the paper was to initiate the efforts of community people including local government on indigenous and local knowledge develop-

  DOI: https://doi.org/10.30564/jgr.v4i3.3223

ment for disaster management. Thus, paper mainly concentrated to document local and indigenous knowledge and practices that are practiced by different communities to predict, mitigate and adapt to hazards in West Seti and Thuli gad watersheds of Sudur Paschim Province where natural hazards like landslides, floods, soil erosion, river bank cutting, debris flow, and seismic activities are frequently occurred .Further, the paper discussed the local heritage and traditions to mitigate and cope the issues climate change induced multi-hazards and socio-economic vulnerabilities. Through inventory of existing practices and their validating process, paper tried to establish their scientific basis for integrating them into science, education, policies, programs and projects for disaster risk reduction (DRR) and climate change adaptation (CCA).

## 2. Methods and Materials

The watershed area was delineated using GIS tools during the field observation stage. Using secondary literature and information biophysical conditions, socio-economic characteristics, infrastructure development stage, natural hazards, vulnerability and disaster risk, and bioresources related information were collected and share preliminary results to the multi stakeholders. Livelihood priorities, threats of hazards, vulnerabilities, and local resources values were identified by location and impact groups; and prepared plans for the key informant interviews (KII), and focus group discussions (FGD). Household (HH) surveys was conducted to assess the differential impacts of various natural hazards and environmental issues that effect on socio-economic life style of the residents of the watersheds whereas FGD for establishing the severity of natural hazards threats and significance values associated with local practices for mitigation of hazards and management of available resources; and KII to explore the causes and intensity of the particular hazards in the watersheds. Risk analysis proforma, guiding checklists designed around DRRM local interest areas, cross cutting areas, were used while conducting surveys including governance, gender and social inclusion and policy.

The consolidated data collected through these methods were presented to group leaders at the exit sharing meeting to provide the participants with a share foundation for identifying and prioritizing DRRM issues in West Seti and Thuli gad watersheds. This was used to identify possible solutions and innovative practices for leveraging knowledge and support through partnerships with local communities, agencies and organizations. All total 380 HHs surveys were conducted in locations that were selected during the field study. The HH survey data were organized into four broad categories: a) natural hazards and vulnerability; b) livelihoods and well-being; c) mitigation measures and resource management practices; and d) promotion of local knowledge for DRRM and climate change adaptation (CCA). The surveys were conducted in locations that were selected using satellite image and meet with local representatives as participants indicated specific issues and challenges appropriate to their respective areas. The detail of the household survey is presented in Table 1.

**Table 1.** Household (HH) surveys by theme and number conducted

| SN | Themes of HH survey | No. HH survey conducted | % |
|---|---|---|---|
| 1 | Natural hazards and vulnerability | 105 | 27.63 |
| 2 | Livelihoods and well-being | 80 | 21.05 |
| 3 | Mitigation measures and resource management practices | 110 | 28.95 |
| 4 | Promotion of local knowledge for DRRM &CCA | 85 | 22.36 |
| | Total | 380 | 100.00 |

*Source: Field study, 2021*



To complement the surveys, we conducted 6 FGDs and 67 KIIs to investigate the key issues identified by households. Citizen scientists were mobilized for conceptualizing the local practices for DRRM and CCA.

Various hazard such as landslide, flood, debris flow and degraded lands were identified through the high resolution recent Google Earth images. Location and area were identified each of the hazard area in the selected municipalities. Among all derived hazard locations, only those areas were selected for field verification, which are more exposed to human settlements. Hazard prone settlements were identified through the location of settlements by near to and severity of the natural hazard. Field verifications were carried out to know the ground reality and their effect on local inhabitants. Reality of hazard and their effect on people were identified on the basis of discussion with local people and observation as well.

The assessment results that inform the collected issues were shared in the sharing meeting. The study team presented preliminary findings and asked the participants to rank these issues in order of importance as well identify as potential actions and outcomes that can be taken to address these issues. The participants were divided into groups to generate potential measures for the effective DRRM and the study team brought the various statements together and synthesized the ideas into the mitigation measures and adaptation strategies. Over all methodologi-


DOI: https://doi.org/10.30564/jgr.v4i3.3223

cal steps and processes are presented in Figure 1.

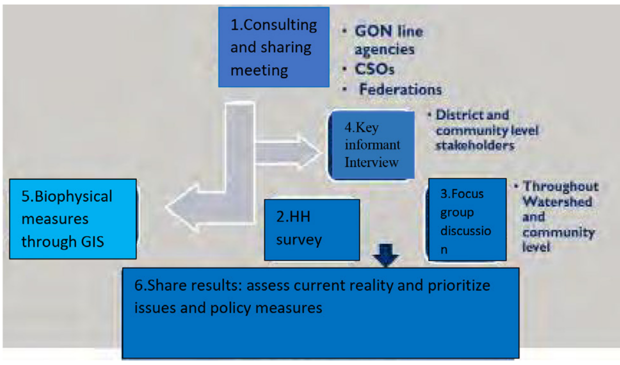


**Figure 1.** Adopted methodology of the study.

## 3. Study Area

The unique geo-tectonic, geological, geomorphologic and climatic conditions of these watersheds are vulnerable/susceptible to various kinds of natural hazards/disasters which have been compounded by increasing human interventions with the nature. Probability of debris flow, mass wasting, landslides, soil erosion, and river bank cutting in both watersheds is very high. In the geological overview, these watersheds occupy a position as harbinger between the Api Saipal and Chandy Himalaya with Karnali river system forming the divide. The rock types vary from highly metamorphosed schists and gneisses to shale and sandstone ranging in age from Middle Pre-Cambrian to Cretaceous. The rocks exposed in Upper Seti watershed belong to Dracula and Surkhet Groups ranging in age from Middle – Late Proterozoic to Lower-Middle Cambrian.

The West Seti watershed sits almost entirely inside Bajhang district with small parts extending into Doti and Bajura. The area is hilly and remote, ranging in altitude from 3,400 m to just 750 m in the southern reaches. The spatial coverage of watershed is 1,488 sq.km and is administered by ten local governments organized according to the new federal structure. Most of the settlements in the watershed inhabit the plains along the Seti River Valley, between 750 m and 2,500 m. Within this range, two annual grain harvests are possible, depending on some geographical and environmental factors (e.g., sunlight, water availability, and soil fertility).

The landscape of the West Seti watershed is visualized into three interrelated themes that influence the dynamism of the watershed. They are nature (environment and natural resources), wealth (socioeconomics and infrastructure: the many ways that people use nature), and power (governance and institutions: the ways that the different people and groups make decisions together about the watershed and its uses) [14]. The analysis draws on multiple data sets associated with these themes to identify critical issues and in terms of its local natural and social dimensions. Then we examine how climate change and other drivers threaten and impact local livelihoods and biodiversity.

The West Seti watershed features a river system fed by rain and snow and comprised of both perennial and seasonal streams throughout. The watershed contains 151 rivers and streams, and seven sub-watersheds with a total drainage density of 647m. The total drainage length of the watershed is 963 km, as the many rivers of the watershed run southward to the confluence with the Karnali River and eventually the Ganges Basin in India. At present Seti West Watershed is more vulnerable for landslides and soil erosion (Figure 2).

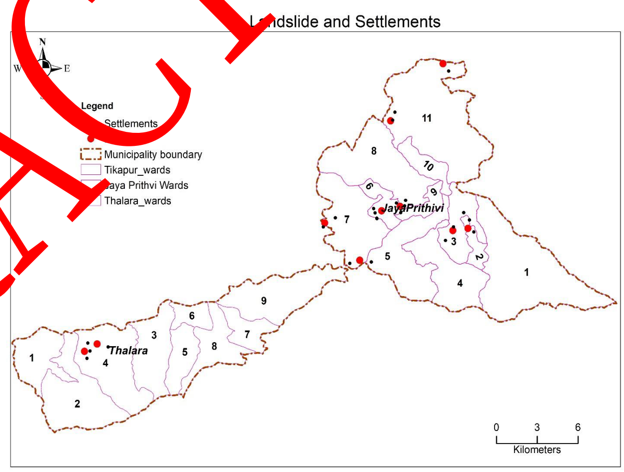


**Figure 2.** West Seti Watershed and Landslide at Badimalika, Bajura where 60 households were displaced after a landslide in July, 2020

The Thuli gad watershed is located within the Karnali River Basin that belongs to parts of Doti and Kailali districts. The watershed stretches across the Jorayal and Badikedar rural municipalities of Doti, and Mohanyal in Kailali. The total drainage density of this watershed is 935 m/km$^3$ and the total area of the watershed is 850 sq.km. Altogether 17 streams and 156 tributaries in this watershed flow into the Karnali River. Water drains from the north between the Karnaso gad of Doti through to the Khimadi near Mohanyal in the south from where it eventually flows into Karnali River (Figure 3&4).



  DOI: https://doi.org/10.30564/jgr.v4i3.3223

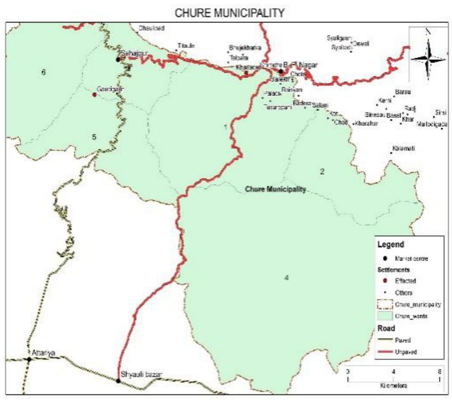


**Figure 3.** Big landslide and river bank cutting at Kimtala, Thuli gad Watershed where both settlement and cultivated land in high risk

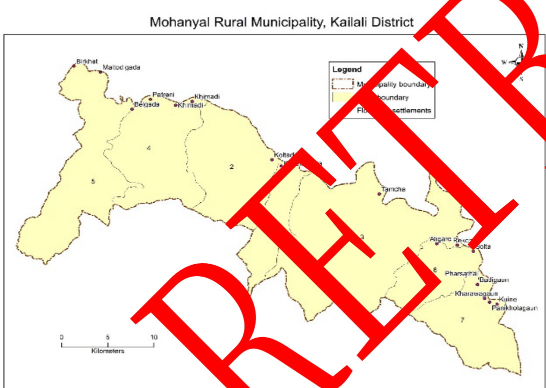


**Figure 4.** Landslides and soil erosion at Thuli gad watershed

## 4. Resources and Hazards

Both watersheds are rich in biodiversity and agricultural land due to the altitudinal gradients in the watersheds, which have produced a wide range of ecosystems from north to south. However, resources like soil fertility and water for irrigation and drinking purposes reported continuously decline since decades. Around 53 percent of households reported having no sufficient water all year round. The overall climate of the watersheds is considered sub-tropical and temperate. At higher elevations, Chirr pine (Pinus roxburghii) trees and other broad leaf tree species predominate in the forests. At lower altitudes, Sal forest (Shorea robusta) is the dominant specie. Due to the steep topography of the watersheds, soil loss and soil fertility rate is observed high than national averages. Furthermore, the rising outmigration of men from the watershed means fewer human resources are available for agricultural work, including soil management. Deforestation and shifting cultivation are two additional challenges to soil retention and fertility in both watersheds.

The design and construction of infrastructure, such as roads and hydropower plants, have an impact on the ecological health of the watersheds if appropriate preventive, mitigated and control measures are not adopted on time. For example, poorly designed rural roads on steep slopes can increase soil erosion and landslides in most of the rural areas of the watershed [15]. Similarly, hydropower plants that divert and impound water restrict the amount of water available for aquatic life that people depend on for their livelihoods. Irrigation canals, while bringing benefits to one group of farmers, can also reduce the amount of water available to other farmers. As demonstrated by these examples, it is important that the design, construction and operation of infrastructure projects account for the full range of social, economic, and environmental impacts within the watershed. Sustainable infrastructure should provide equitable distribution of benefits with minimal long-term, environmental impacts.

Regarding the land use pattern, there are four major types of land cover in the West Seti and Thuli gad watersheds more than 78 percent under forest, 19 percent under cultivated land, 2 percent under rivers and streams and rest portion under other wooded land and shrubs. Agriculture is the most common livelihood and out of total cultivable land around 37percent land dedicated to crops with 15 percent permanent irrigation) facility. Rice, maize, wheat and millets are the main cereals. Overall, we find decreasing river discharge during pre-monsoon, monsoon, and post-monsoon precipitation has decreased in these watersheds while temperatures have increased, and it is believed these are the two main drivers of the decreasing river discharge.

### 4.1 Availability of Drinking Water

In terms of social composition, the watersheds are widely varied in terms of ethnic origin, mostly Brahmin, Chhetri, Dalits, Magar, Lama, Bhote, Gurung, Newar, and Tamang. Major settlements are primarily composed of Brahman/Chhetri, Dalit, and Magar.

Household surveys conducted during march-April, 2021 (n=380) found that less than 65percent households obtain sufficient daily water within 30 minutes of home, while 15 percent require between 30-60 minutes, and 13 percent require more than an hour. Around seven percent families have private taps, therefore no travel is necessary for collection. Sixty percent households have access to piped tap systems followed by stream/river (11.2%), spout water (9.4%), uncovered well (10%) and rest others. The water supply for the piped systems comes primarily from springs (89.3%) while another 10.7% draw piped water directly from the river. In terms of water access, 82 percent of respondents said they had equal access to available sources while 18 percent said they did not have equal access. Ninety percent of water sources are public, and the rest are private.

### 4.2 Disasters and Social Vulnerability

During the field study an effort has been made to take the critical feedback and suggestions with the participants to identify priority issues and actions, and for promoting local practices on watershed management and disaster risk reduction. The representatives of elected local bodies also expressed eagerness to allocate their resources in support of activities in all aspects of watershed conservation and disaster risk reduction management. Most of the area of these two watersheds stretches from plains in the south to hilly areas in the center of the province. The watersheds have been faced many challenges, among them the construction of improperly designed roads and variability in climatic patterns. Table 2 summarizes the prioritized issues by the key informants and FGD participants in the area.

**Table 2.** Impacts of natural hazards by prioritized issues

| SN | Prioritized issues | Impacts |
|---|---|---|
| I | Climate-induced hazards such as landslides, flooding and sand deposition | Loss or degradation of natural habitats reduces the number of natural resources available for local populations, such as declining fish populations and decreasing water availability. Landslides and flooding exact loss of property, infrastructure and human life. |
| II | Drying water sources | As water sources dry up, there is less water available for drinking, sanitation, and agriculture, and aquatic habitats are degraded. Additional investments are needed to improve water distribution and encourage adoption of modern technologies to improve efficiency of water use. |
| III | Flood and inundation | Flooding and sand deposition are the major threats to both human and ecological communities. Floods and landslides, further aggravated by the construction of improperly designed roads, pollute water bodies and damage natural habitats of freshwater biodiversity. |
| IV | Degradation of watershed resources | Watershed degradation leads to forest, water and soil quality decline and local community face the scarcity of livelihoods i.e., Food, Fuel and Fodder (F3) further leads outmigration from the watersheds. |
| V | Prolonged drought | Prolonged drought contributed to the drying up of springs and other water resources specially in Siwalik foothills in Jorayal and Badikedar Gaupalika in Doti and Mohanyal and Chure Gaupalika in Kailali. It was due to improperly constructed roads and climatic changes accelerate. |
| VI | Forest degradation and wildfires | Available timber and non-timber forest products decline, negatively affecting livelihoods and food security. Root systems that store water and stabilize slopes are weakened, increasing the likelihood of erosion and landslide. Risk of wildfires increases. |

*Source: Field study, 2021*



DOI: https://doi.org/10.30564/jgr.v4i3.3223

As reported by the stakeholders there are many climatic induced hazards both in West Seti and Thuli gad watersheds. At the same magnitude in Mahana watershed occurred last monsoon at Gundi, Chure Rural Municipality Ward-5 (Figure 5).

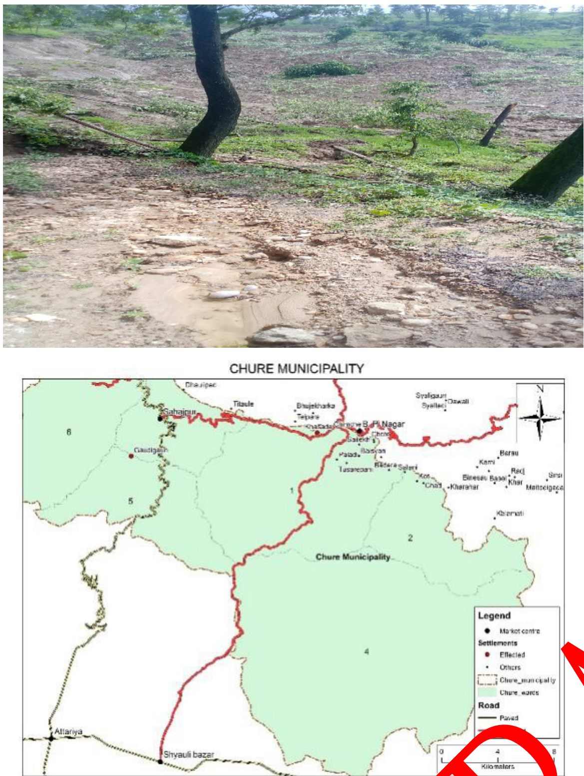


**Figure 5.** Landslide at Gundi, Chure-5

Figure 5 depicts the magnitude of Patreni landslide at Gundi Simal Gaira-5, Chure Rural Municipality which is located in Mohana watershed area. Big landslide incident occurred in July, 2020 and 45 households were displaced and took shelter in Chaumala. Ward chair reported that due to the sensitive area for landslide hazards more than 600 households had already left that area and resources need to settle them adopting integrated settlement development program in a safer area.

## 5. Perceived Mitigative Measures

Discussions with government officials, elected representatives, social and environmental activists and media persons as KII to suggest the remedy measures for rapid degradation of watershed resources, ever increasing natural hazards and growing challenges of livelihoods in Seti and Thuli gad watersheds, they suggested many preventives as well as mitigative measures for the effective disaster risk reduction management and sustainable management of watersheds resources. Most of the key informants stressed on government supports for local skills and techniques for retaining runoff water on site which will reduce erosion and protect agricultural land in upstream of the watersheds while FGD participants focused to encourage locally initiated and low-cost bioengineering and river bank management system and raise awareness to manage bushfire and open grazing through community users' groups by linking it with community livelihoods. However, elected representatives of municipal level as well as ward level viewed that need is to produce and disseminate communication materials and e-programs on best practices for disaster preparedness planning, disaster reduction, livelihood improvements, available herbal and aromatic as well as no-timber forest products (NTFPs) conservation, cultivation, processing and marketing for the long- term sustainability of local communities without any disasters. Government officials and I/NGOs representatives suggested to support for establishing and strengthening early warning system (EWS) at community level and improve implementation of environmental resource management plan (ERMP), disaster preparedness and response plan (DPRP) and local disaster risk. Personally, chairperson of Chure Rural Municipality pointed out that conservation of watersheds and wetlands is a prime task to reduce the multi-hazards like landslides, floods and soil erosion and strictly control and regulate extraction of river materials in upstream and downstream areas of watersheds.

**Photograph 1.** Discussion with Chairperson of Chure Rural Municipality at disaster management information center, Shivanagar-1

Majority of the respondents further emphasized to relocate scattered and sensitive areas settlement in a safe location with modern facilities and construct shelter houses out of the floodplains and other vulnerable areas. They also suggested to improve implementation of water use master plans (WUMPs); implement low-cost techniques that stabilize slopes and riverbanks; adopt modern and simple technologies, such as solar water pumps, Dhiki pumps (treadle pump), drip irrigation, and rainwater harvesting.

The representatives of civil society and social activists including school teachers opined to encourage enforcement of existing laws and regulations related to watershed conservation and management, to conduct advocacy, training, and capacity building at the local level by including civil society (CS), community-based organizations (CBOs), community forest user groups (CFUGs), buffer zone management committees (BZMCs), and buffer zone community forest groups in creating plans for community resilience building (CRB). They further argued to initiate dialogues between and among the local province and federal government level agencies and between government and non-governmental agencies; promote ecotourism (e.g., sport fishing, rafting, and river beach programs), and promote local resource- based enterprises by providing adequate financial and technical supports to the local community for safety and wellbeing community life in disaster affected areas.

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## 6. Innovative Practices for Disaster Reduction

As climate change induced natural hazards impacts continue to influence on resource degradation and socio-economic vulnerabilities in the West Seti and Thuli gad watersheds. Efforts made by governments and non-governmental organizations seem ineffective to anticipate and address these challenges at the community level. Government officials to water, forests and soils, several civil society organizations have been engaged to strengthen their livelihoods against threats of natural hazards and climatic variability. However, community lives are in high risk of multihazard and socio-economic vulnerability. The reason behind their inactive role in government led actions and programs is probably not to consider their traditions, knowledge and skills to reduce the risk of disasters and manage their livelihood resources. Thus, this study made an effort to cope their knowledge, ideas, skills and novel practices during the events of natural hazard and to document their innovative opinions for future planning strategies in the field of disaster risk reduction management and sustainable livelihood improvement in hazard prone areas. In response the local people in Jaya Prithvi Nagarpalika said that community resource plan needs to implement in disaster mitigation measures and integrate it with each infrastructure project undertaken in the future. They clarified that for every road built, the government should allocate money for earmarked and erosion control measures such as Gabion boxes. Similarly, In Chure Gaupalika, respondents opined that the infrastructure development budget has to cover construction-led disaster mitigation measures.

Whereas key informants in Sahajpur and Khanidada viewed that governance and its responsiveness has to towards community needs and aspirations for managing local resources sustainably, strengthening community resilience, and conserving biodiversity. Elected representatives of Badikedar Rural Municipality of Doti and Mohanyal Rural Municipality of Kailali emphasized on active participation of local communities in the planning process to mobilize the powers and functions relating to local level disaster preparedness and response planning, early warning systems, and distribution and coordination of relief materials. But site observations and focus group discussions also revealed that almost all local government units i.e., urban municipality and rural municipality authorities have been executing these powers related to disaster management with less emphasis on conservation of resources, promotion of local skills and practices and enough resources have been devoted to construction works and relief (confronting objectives) distribution [16]. Though Constitution of Nepal provides local government authority to oversee management of forests, watersheds, wetlands, wildlife, birds, and bi-diversity. However, given the current transition to this federal structure, some of these rights and duties have yet to be exercised and discharged by the local governments [17].

Respondents expressed their growing awareness of the need to develop strong relations between upstream, middle-stream and downstream communities, and to understand the interconnection between upstream- downstream geomorphic process and events. They advised to sustainable conservation of upstream biophysical resources is a prime task to control downstream drought and flood hazards. Deforestation and destruction in highland due to unscientific road tract construction led to landslides, soil erosion in Chure range and steep hillslope area and consequently flash flood in low river basin. In spite of the many regulations providing working guidelines to promote local skills and technology for local resources conservation and utilization with low risk of hazards, there is a lack of implementation of community participation activities that lead to community initiations for safer lives and better outcomes [18].



DOI: https://doi.org/10.30564/jgr.v4i3.3223

Respondents reported that coordination among local governments, district coordination committee, and province government is very low. Representation of women and marginalized community people also found low formal and informal committees, and organizations. Building consensus and ownership between government and local communities is the worst condition. However, the participants of FGD and Key informants in Thuli gad watershed stressed that coordination among communities and three-layer government is essential to create favorable condition for the resource conservation and promoting community resilience Stakeholders in both watersheds were asked to list their concerns about natural hazards, risk management and livelihoods. In response, stakeholders raised the issues of rapidly degradation of natural resources to support their livelihoods, devastating hazards like large scale landslides, huge amount of soil erosion, flash floods and droughts, growing unemployment trends and migration of youths in search of job and growing scarcity of daily life resources like water, forest and food grain production. Raised issues by stakeholders are summarized in Table 3 with their ranking.

After listing the issues related to scope, severity and local interest, participants were assigned to prioritize issues based on their perceptions of urgency in the need to address. Each participant was allowed to prioritize up to three issues, although many prioritized only two or one. Gender balanced was properly maintained to avoid the potential influence across gender. It(Gender case) was undertaken to collect the views and opinions about the local environments the severity of environmental degradation specifically from women and marginalized community people because women and marginalized community people have more dependency on environmental resources and they also highly affected by climate change induced disasters. The exercise revealed that local stakeholders have had significant concern for disaster risk reduction management, local initiations for available resource management, discouraging unscientific and unplanned construction works and improvement of community livelihoods by promoting local resource and technique-based entrepreneurship.

Regarding the local knowledge promotion for disaster management and sustainable livelihood improvement in multi-hazard prone area's communities, respondents suggested to develop intercommunity and interinstitutional synergies and associations nationally as well as locally through academic and cultural collaborations. They viewed that such collaboration could facilitate both academic programs and local development agencies by the fusion of cultures and fostering minds through regional exchanges and cooperation in form of educational, research and development activities(19,20). This mechanism can promote a spirit of cultural awareness, adaptability and enhancing the transversal skills of its local people and academicians. To address the local, national

**Table 3.** Environmental issues by their rank

| SN | Issues | Female | Male | Total | Ranking |
|---|---|---|---|---|---|
| 1 | Unplanned expansion of rural roads | 4 | 20 | 24 | Very high |
| 2 | Droughts and diminishing water | 9 | 14 | 23 | Very high |
| 3 | Degradation of wildlife habitats, decline in number and species of wildlife | 9 | 8 | 17 | Very high |
| 4 | Forest degradation due to open grazing and forest fires | 2 | 12 | 14 | Very high |
| 5 | Loss of agriculture due to landslides and river cutting | 1 | 9 | 10 | High |
| 6 | Unsustainable resin collection | 5 | 7 | 12 | Very high |
| 7 | Gravel mining and collection | 6 | 10 | 16 | Very High |
| 8 | Loss of property due to landslides | 5 | 8 | 13 | Very high |
| 9 | Threats to traditional livelihoods | 6 | 5 | 11 | Medium |
| 10 | Conflicts over water us | 8 | 4 | 12 | Medium |
| 11 | No collaboration between upstream and downstream communities | 5 | 12 | 16 | High |
| 12 | Unmanaged solid waste and drainage system | 2 | 3 | 5 | Low |

*Source: Field study, 2021*

and global challenges like environmental degradation, climate change, devastating disasters, poverty, inequality, peace and justice, practicable education program needs to implement from basic level to higher level to make safe, resilient and productive human community.

## 7. Conclusions

Climate induced natural hazards like landslides, drought and floods generated by extreme weather events and excess anthropogenic activities on fragile middle hells and Siwalik foothills which continue to have negative impacts on the people and economy of the province. The poor communities in the province are more affected and in vulnerable conditions due to the loss of their properties and compel to be displaced from the birth place in search of safe area for shelter and livelihood options. They are also lacking capital assets and other vital institutional support needed for their sustainable community lives in the area where disasters are rising on. Low levels of socio-economic life standard of these communities, the ongoing depletion of natural resources; lack of cultivated land and livestock raising; and inadequate financial services (in the form of microcredit, micro insurance and micro savings) limits their livelihood options and strategies. These communities are facing the disaster related life challenges and in unbearable conditions from every year occurred extreme weather events and natural hazards. Government initiations also appear insignificant level for disaster reduction and safety life of the affected communities in almost area of the province. This situation clearly appeals to implement measures that could build the capacity of communities by raise the awareness level and also empower them by enhancing capital asset accumulation, increase institutional support and the role of educational institutions for the effective disaster management local practices and climate change adaptation capacity building. Thus, all level governments need to provide required technical, financial, institutional and policy supports to make them safe from disasters and economic hardship. This can be achieved through policy formulation and action by the three level governments to provide the people access to technical skills, policy support and capital assets.

## Acknowledgments

Authors wish to thank the UGC-Nepal for the financial support of the study and authors are also thankful to the Dean, Faculty of Education, Tribhuvan University and his staff, for the valuable advice and support in the study. Authors would like to acknowledge local people for their help during the field study which made us to complete the study in time successfully.

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ARTICLE

# A Climatology of Heavy Rain and Major Flood Events in Victoria 1876-2019 and the Effect of the 1976 Climate Shift

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ARTICLE INFO

*Article history*
Received: 7 May 2021
Accepted: 7 June 2021
Published Online: 11 June 2021

*Keywords*:
Low pressure systems
Tropical interaction
Warm air advection
Southern oscillation index

ABSTRACT

An extensive search has been carried out to find all major flood and very heavy rainfall events in Victoria since 1876 when Southern Oscillation (SOI) data became available. The synoptic weather patterns were analysed and of the 319 events studied, 121 events were found to be East Coast Lows (ECLs) and 82 were other types of low-pressure systems. Tropical influences also played a large role with 105 events being associated with tropical air advecting down to Victoria into weather systems. Examples are presented of all the major synoptic patterns identified. The SOI was found to be an important climate driver with positive SOIs being associated with many events over the 144 years studied. The 1976 Climate Shift and its influence on significant Victorian rainfall events is studied and negative SOI monthly values were shown to dominate following the Shift. However, one of the most active periods in 144 years of Victorian heavy rain occurred after the shift with a sustained period of positive SOI events from 2007 to 2014. Therefore, it is critical for forecasting future Victorian heavy rainfall is to understand if sequences of these positive SOI events continue like those preceding the Shift. Possible relationships between the Shift and Global Temperature rises are also explored. Upper wind data available from some of the heaviest rainfall events showed the presence of anticyclonic turning of the winds between 850hPa and 500hPa levels which has been found to be linked with extreme rainfall around the Globe.

## 1. Introduction

In 2017 [1] showed a marked fall in Victorian rainfall over the period 1986 to 2015 driven primarily by a reduction in the cool-season (April to October) rainfall. [2] in 2019 also addressed this problem. In this study a climatology of intense Victorian rainfall events since 1876 is presented to examine this change as well as identifying the weather systems involved along with their vertical structure and possible large-scale influences.

In this study we took advantage of a Victorian Government list of major floods available on the web: http://www.floodvictoria.vic.gov.au/centric/learn_about_flooding/flood_history/pre_1900_floods.jsp.

This list finished in 2007 and we added events after this from Bureau of Meteorology records after 2007. We then began a search for further events to account for possible omissions in the Victorian Government lists or potentially major impact events which didn't quite meet the River height criteria to be classed as major floods but had a

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DOI: https://doi.org/10.30564/jgr.v4i3.3204

huge impact. The main source of known impacts came from a search of the Archives of the Melbourne Argus, Melbourne Age and Gippsland Times and other Regional Newspapers which are available at https://trove.nla.gov.au/newspaper covering the period 1860 to 1957. The search also involved looking for events which were associated with record Victorian rainfall or widespread heavy rainfall (daily totals to 100mm or more). We also added to this group events classified as major from various Local Government Reports available on the web but not recorded in the SES list. From analyzing the impacts of these additional events, we selected the high impact events as unofficial major floods.

There are now two lists:

A list of all known events numbering 389 describing the impact and synoptic situation where possible.

This list was reduced to 319 strong impact events between 1860 and 2019 for the Victorian region.

A copy of the list can be obtained by emailing jeffjcallaghan@gmail.com .

Section 2 of this paper describes the various sources of data used in the Study. Section 3 illustrates the changes to river hydrology which is experienced over long periods using the Yarra River as an example. The method of rating floods is covered in Section 4 while a climatology of Victorian heavy rainfall and major flood events is examined in Section 5. This includes the role of the SOI and effects of the 1876 Climate Shift. Examples of synoptic weather types causing major flood events are provided in Section 6. The vertical structure of the heaviest rainfall events is examined in Sections 7 Mechanisms were described in Section 8 while a conclusion is reached in Section 9.

## 2. Data Sources

In this report we have used data from the Bureau of Meteorology and data from the National Centres for Environmental Prediction/ National Centre for Atmospheric Research (NCEP/NCAR) Reanalysis Project, which were available at: https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html.

Early mean sea level pressure (MSLP) analyses were obtained from Bureau of Meteorology charts published in various newspapers, the earliest being from 1910 in the Sydney Morning Herald.

These can be found at https://trove.nla.gov.au/newspaper which we mentioned above as the main source of impacts. Prior to this an excellent record of Australian charts and detailed newspaper description of significant weather was created by the Meteorological pioneer Sir Charles Todd (Chief Astronomer of South Australia). These charts extend back to 1879 and can be found at www.charlestodd.net/Todd_Hi-Res/.

Earlier charts were created using official meteorological observations published in the newspapers at the time.

Of the 319 events list between 1876 and 2019 the following are the associated synoptic weather patterns:

East Coast Lows (ECL) 121

Low pressure systems 82

Tropical interaction: -

Troughs or fronts with tropical inflow 58

Lows with tropical inflow 31

Extra-tropical transition of a tropical cyclone (ET) -1

Strong NE winds 1

Tropical Lows 14

Total Tropical Interactions 105

Fronts 10

Trough 1

There has been a tendency for the occurrences of ECLs to increase since 1945. This was discussed in [3] Callaghan 2019 however with more intensive digging older ECL events were unearthed so the trend is still there but not as great. There were 51 ECL events from 1876 to 1944 (69 years). There were 34 ECL events from 1945 to 1976 (32 years) and 41 ECL events following 1976 (44 years) that is a total of 71 events in 76years. The year 1976 was marked by a Global Climate Shift (see below).

## 3. Changes to the Hydrology of Rivers over Time

River floods have been mitigated over the period of our study by increasing discharge rates through dredging and removing rock outcrops etc., and by building dams to store flood waters. This mitigation has been offset to some extent by an increase in urban runoff, caused by growth in urban areas, especially during the last forty years. Dams have been constructed throughout the study region.

As an example, below are documented changes to the Yarra River since 1849:

### 27-29 November 1849

A flood is exceeded by several feet any flood of former years. The weather-gauge at the Flagstaff (Melbourne) indicated a fall of 175 mm of rain on Tuesday 27 November 1849. Twelve people were drowned in the Yarra and Maribyrnong River floods. In Melbourne (CBD) at 1800 UTC 27 November the flood was at its greatest height. The wind and storm surge reports indicated that an intense low caused the floods. At Collingwood there was considerable wind damage with large trees, fences and chimneys blown down and at Williamstown a storm surge flooded farms to a depth of 60 cm. Serious flooding also occurred


DOI: https://doi.org/10.30564/jgr.v4i3.3204

in Gippsland indicating the low moved east along the Victorian Coast.

### 1863 Flood

This flood is considered the largest on record. There was ten feet (3.05 metres) of water in the closed bar of the Sir Henry Barkly Hotel Richmond. At Hawthorn the river rose between thirty and forty feet (9.14 to 12.19 metres) higher than during the great flood in 1849. In the city the flood attained only a lesser height than in November 1849, however between 1849 and 1863 the river had been enormously deepened by artificial means, and thus a very much greater body of water could pass seawards than was the case at the period of the great flood of fourteen years earlier.

### 1891 Flood

At the Johnston Street bridge the water reached 41 ft (12.50 metres) above summer level. Mr. Ellery, the Government Astronomer at the time, concluded that the 1891 flood was a little higher, perhaps about 6inches (15.2 cm), than that of 1863 due to changes at Richmond discussed below.

### Reduction of Flood Levels in 1891

Whatever damage was done by the 1891 floods it was at the time considered certain that it would have been far greater had it not been for the vast improvements in the river affected by the Harbour Trust. The trust undertook to make these improvements in 1887 and spent large sums of money with apparently excellent results. The Falls at Market Street in the City were entirely removed. This was a raised rocky causeway, which could be crossed in the summer months almost without wetting the feet, and it was converted into navigable water 16 ft (4.88 metres) deep at low tide.

### Higher Levels at Richmond in 1891

The Floods Inquiry Board, appointed after the 1891 disaster came as a result of very careful investigation to the determination that the flood of 1891 was is in volume about two thirds of that of 1863 and yet at several points by comparison with such levels as still remained it was determined to have been higher than that of 1863. After much enquiry and doubt, the reasons for this were found in the fact that certain railway and road embankments, especially the approach leading to the Botanical Gardens bridge which had been completed since 1863, had thrown the water back on Richmond. The building of such masses of cottages and houses on the Richmond flat presented to the outpour of the water more obstructions which did not exist in 1863. All those were the reasons of the higher levels.

### 1901 Flood

William Davidson, inspector general of public works said in 1901 “If rainfall returns are any indication the water passing down the Yarra in 1901 was equal to the volume in 1863 and one third in excess of the volume in 1891. The 1891 flood the water rose to about 8ft (2.44 metres) in the bar of the Sir Henry Barkley Hotel in Punt road. In 1901 the water had 3feet (0.91 metres) to 3feet 6inches (1.07 metres) to rise to get to the floor of the bar. The flood level at that time was, therefore, at least 11 feet (3.35 metres) lower than at the maximum of the flood of 1891.” The reasons for the vast reduction of the 1901 flood levels resulted from the widening and deepening the river from Princes Bridge to a point beyond the South Yarra railway bridge which was recommended following the 1891 floods.

Between 1924 and 1929, the Melbourne and Metropolitan Board of Works removed 24,400 items of natural debris from the river to improve flood control and navigation. In 1929 a severe loop in the river at Burnley was eliminated by cutting a canal to make a straight, wide section. Herring Island was created in the process. The Yarra’s last great flood was the one in 1934 which reached 12.05 metres at the Johnston Street Bridge compared with 12.50 metres in 1891 when the river was much more likely to flood. The conditions in 1934 are apparently similar today. So, an event such as the one in 1934 represents the worst known event for flooding in Melbourne. However further upstream the upper Yarra Reservoir was completed in 1957, initially for the purpose of preventing flooding downstream.

## 4. Rating of Flood Events

The probability of a flood level being equalled or exceeded in any 1-year period can be expressed as a percentage, the annual exceedance probability or AEP, or as an average recurrence interval, or ARI. As an example, take a flood level which can be expected to be equalled or exceeded on average once every 100 years. In this case, the ARI is 100 years and the AEP is 1%. It is important to note that an ARI of, say, 100 years does not mean that the event will only occur once every 100 years. In fact, for every year there is a 1% chance (a 1 in 100 chance) that the event will occur. The use of annual exceedance probability (AEP) to describe the chance of a rainfall amount is generally preferred as it conveys the probability or chance

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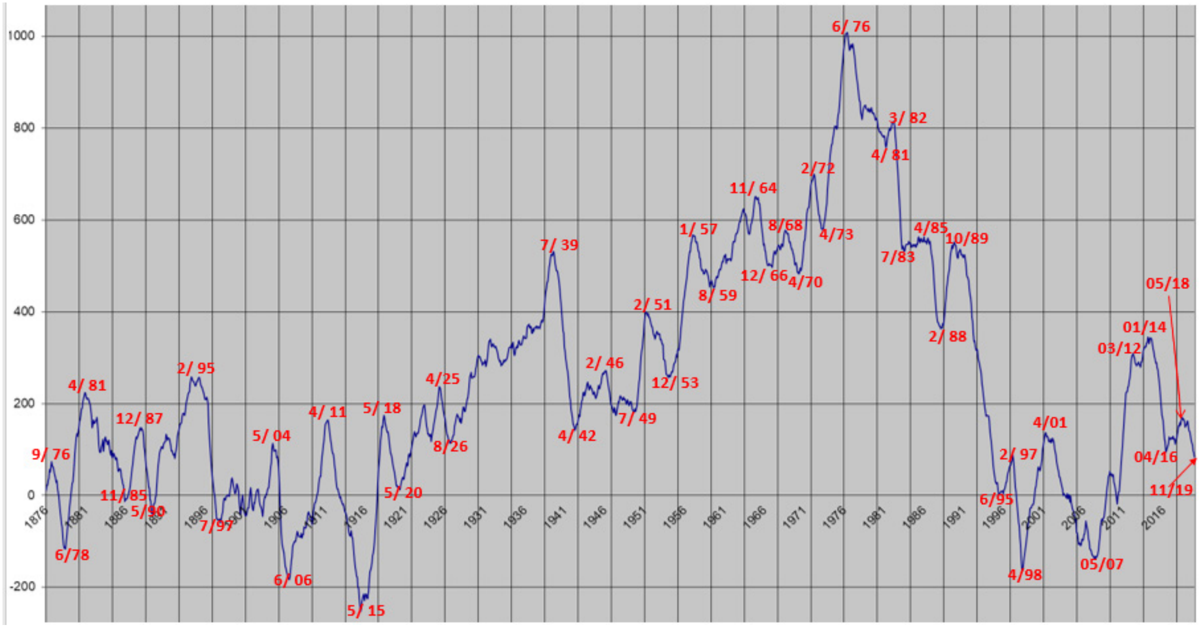


**Figure 1a.** Cumulative Southern Oscillation Index January 1876 to November 2019. Red numbers show the month and last two digits of the year.

that exists for each year. The alternative, ARI, is a term which is easily misunderstood however it is more widely used and appears to be favoured by the public, so we use it here as well as the AEP.

## 5. Climatology

For a summary of Victorian climate in general see the Bureau of Meteorology web site Climate of Victoria (weather-climate.com).

The cumulative Southern Oscillation Index (SOI) is shown in Figure 1. To generate this curve the monthly value of the SOI is continually added so for sustained positive values the curve rises and for negative values it falls. Events shown in the list are analysed using this cumulative SOI curve. Below rising (positive) SOIs are highlighted in red while falling (negative) values are blue.

Lists of event sequences during different phase of the SOI red is positive and blue is negative.

Jan 1876 to Sept 1876 zero events
Oct 1876 to June 1878 1 events
June 1878 to Apr 1881 4 events
Apr 1881 to Nov 1885 4 events
Nov 1885 to Dec 1887 4 events
Dec 1887 to May 1890 6 events
May 1890 to Feb 1895 9 events
Feb 1895 to July 1897 5 events
Aug 1897 to May 1904 10 events
Jun 1904 to Jun 1906 2 events
Jul 1906 to Apr 1911 16 events
May 1911 to May 1915 4 events
Jun 1915 to May 1918 8 events
Jun 1918 to Apr 1920 4 event
May 1920 to Apr 1925 9 events
Apr 1925 to Aug 1926 3 events
Sept 1926 to Jul 1939 41 events
July 1939 to Apr 1942 one event
May 1942 to Feb 1946 3 events
Mar 1946 to July 1949 6 events
Jul 1949 to Feb 1951 5 events
Mar 1951 to Dec 1953 11 events
Dec 1953 to Jan 1957 17 events
Feb 1957 to Aug 1959 2 events
Sept 1959 to Nov 1964 10 events
Dec 1964 to Nov 1966 2 event
Dec 1966 to Aug 1968 2 events
Sept 1968 to Mar 1970 4 events
Apr 1970 to Feb 1972 9 events
Mar 1972 to Apr 1973 2 Events
Apr 1973 to Jun 1976 13 events
July 1976 to Jan 1988 15 events 8 of these –ve IOD
July 1983 to Apr 1985 6 events
May 1985 to Jan 1988 8 events 3 of these –ve IOD
Feb 1988 to Oct 1989 5 events
Nov 1989 to May 1995 15 events 8 of these –ve IOD
June 1995 to Feb 1997 6 events
Mar 1997 to Apr 1998 zero events
May 1998 to Apr 2001 7 events
May 2001 to May 2007 5 events

May 2007 to Jan 2014 26 events
Feb 2014 to Apr 2016 2 events
May 2016 to May 2018 7 events
June 2018 to Dec 2018 1 event

From this between 1876 and 2019 there were 210 positive events and 109 negative events which clearly shows that heavy rain and flooding in Victoria are more likely in positive phases of the SOI. From July 1976 some events are highlighted which occurred during negative phases of the Indian Ocean Dipole (IOD) which is discussed below.

## Interdecadal Pacific Oscillation and major events coinciding with major Global Temperature rises from 1915 to 1939

From [1] sustained positive SOI episodes occur during negative phases of the Interdecadal Pacific Oscillation (IPO) and they state that current understanding of the IPO doesn't enable a decision on whether pre 1976 Climate Shift sequences of numerous SOI positive episodes will resume.

Coinciding with strong Global temperature rises with only moderate Global Carbon emissions were a series of strongly positive SOI episodes where from May 1915 to July 1939 when the monthly average SOI was +2.7. From May 1915 to July 1939 there were 58 events during the positive phases of the SOI and 7 events during the negative phases. This period was also very active in other regions for example from June 1915 to July 1939 Nineteen Tropical Cyclones (16 of which occurred during positive phase of SOIs) impacted on the coast north of Brisbane. Of these the following major cyclones occurring during positive phases of the SOI, 1916 Whitsunday Severe tropical cyclone 62 lives lost in Clermont, 1918 Severe tropical cyclone Mackay 30 lives lost, 1918 Severe tropical cyclone Innisfail 77-97 lives lost; 1927 Severe tropical cyclone 47 lives lost and 1934 Severe tropical cyclone Port Douglas 79 lives lost. Over the same time there were 28 major impact events causing severe coastal damage between Brisbane and the Victorian Border (Callaghan 2019) and 26 of these occurred during positive phases of the SOI.

Despite these large sequences of devastating events occurring during sustained periods of positive SOIs this period has been classified as a positive phase of the IPO [4]. This does not seem to be logical considering other positive phases of the IPO. It would appear this classification of the IPO is in error or our understanding of the IPO is in error.

## Negative IPO 1945-1976

This IPO produced 58 Victorian events when the monthly SOI was positive and 27 events with a negative SOI. Over the same time there were 70 major impact events causing severe coastal damage between Brisbane and the Victorian Border [5] and 45 of these occurred during positive phases of the SOI. This is what we have come to expect during negative phases of the IPO. From the late 1940s to the 1976 shift when the monthly SOI was averaging +2.5 the global temperatures fell as Global Carbon emissions began to increase dramatically (Figures 1b and 1c). This halted the earlier period of strong Global temperature rises from around 1910.

## The 1976 Climate Shift and Victorian Heavy rainfall.

Note the marked change in the cumulative SOI in Figure 1 where the graph sharply turns from rising to falling in June 1976. This has been called the 1976 Climate Shift [6]. As the curve plummeted in Figure 1a following the Climate shift there was a marked change in Global climate producing high impact long lasting events all over the Globe. Severe Extra-Tropical cyclones lashed California, for example [7,8] there was extreme beach erosion in California in the 1982/1983 and the 1997/1998 El Niño events. There was a Massive rise in the Caspian Sea (see Figure 1d) in the 20 years followed the shift. Extensive beach erosion occurred in coastal Brazil (G Buden personal communication) over the twenty-year period following the Shift and in sub-tropical eastern Australia a long-term tropical cyclone hiatus began [10,11]. Rainfall was markedly reduced in New South Wales [12] in the 20 years following the shift. There was an unprecedented number of El Niño events following the Shift and five of these produced very dry conditions in Victoria, 1982-83,1997-98, 2002-03, 2006-07 and 2015-16. Three produced partly dry conditions in Victoria 1991/92, 1994-95 and 2009-10, and two had little effect on Victoria 1987-88 and 1993-94.

However, conditions recovered with a major strong La Niña event in 2010-12. The years 2010 and 2011 ranked third and second as the wettest calendar years for Australia, with 703 mm and 708 mm respectively, both well above the long-term average of 465 mm. Combined, the two events yielded Australia's wettest 24-month period on record. This contributed to the most active period in the Victoria record when from May 2007 to January 2014 where there were 26 events and from Figure 1a the graph was mostly rising (SOI positive) over this interval. The critical factor for Victorian heavy rainfall is whether sustained positive SOI episodes resume like those preceding the Climate Shift. Following the climate shift there were 57 positive events and 46 negative events which suggests a much weaker influence from the SOI. This occurred as

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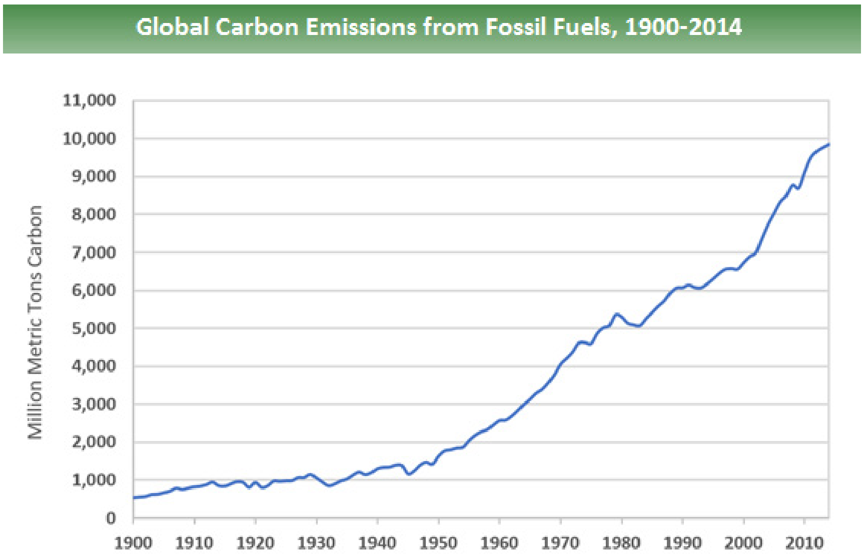


**Figure 1b.** Global, Regional and National Fossil-Fuel $CO_2$ Emissions [14]

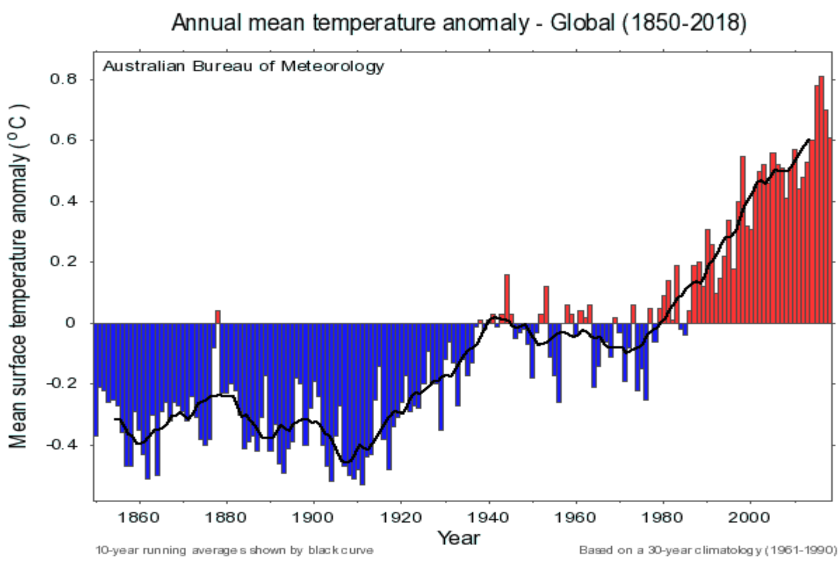


**Figure 1c.** Global annual mean temperature anomaly 1850-2018 with 10 year running average marked by bold black curve.

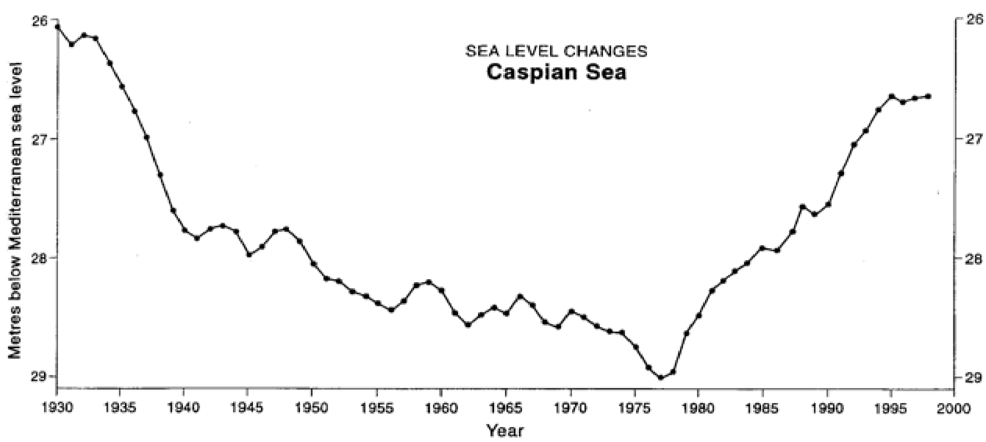


**Figure 1d.** Sea level rides Caspian Sea after Climate Shift from [9].

negative SOI episodes were more prevalent following the climate shift. From July 1949 to June 1976 the monthly average SOI was +2.5 and following the Climate Shift from July 1976 to April 1998 the monthly average SOI was -4.5. Overall, the Climate shift affected the number of Victorian events occurring. From May 1950 to the Shift they occurred at a rate of 2.7 events per year and after the shift at a rate of 2.3 events per year. The number of events post Shift was helped by the number of events generated by negative Indian Ocean Dipole (IOD) effects (see below) and a strong La Niña. Before and after the Climate shift there was a complex interaction with Global temperature tendencies and Global Carbon emissions. Following the Shift up to 2000 the strong Global temperature rises resumed, this time under strong carbon emission increases (see Figure 1b).

The number of Victorian flooding events with a negative SOI were increased after the shift under the influence from negative Indian Ocean Dipole (IOD) episodes.

IOD data is available at https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/Data/dmi.long.data

Intensity of the IOD is represented by anomalous SST gradient between the western equatorial Indian Ocean (50E-70E and 10S-10N) and the south eastern equatorial Indian Ocean (90E-110E and 10S-0N). This gradient is named as Dipole Mode Index (DMI). When the DMI is positive then, the phenomenon is referred as the positive IOD and when it is negative, it is referred as negative IOD which results in increased rainfall over Victoria. Of the 15 negative SOI events from July 1976 to June 1983, 8 occurred during negative IOD episodes. With the 23 negative SOI events from May 1985 to May 1995 again 11 occurred during negative IOD episodes. This is unusual as research has shown that the IOD events are generally not independent of ENSO variability [13]. Most positive IOD events tend to occur during El Niño events while negative IOD events dominate during La Niña [15]. Victoria experiences widespread rainfall and its wettest conditions when La Niña aligns with a negative IOD as happened during the spring and summer of 2010 - 2011 that ended the Millennium Drought [15,16]. Conversely, the driest condition prevails when a positive IOD co-occurs with El Niño. Hence, they act together either to significantly reduce or amplify rainfall over Victoria.

### Droughts

Three prolonged periods of below-average rainfall occurred during the instrumental period [17]: The Federation Drought (1896 – 1905), the World War II Drought (1936 – 1945) and the Millennium Drought (1997 – 2009), each with different characteristics [17,18]. During these drought years heavy rain/flood events continued in Victoria. In the 1896 – 1905 drought there were 12 events in Victoria, during 1936 – 1945 there were 13 events and during 1997 – 2009 there were 16events. During these three drought these Victorian heavy rain events occurred at the rate of roughly one event per year against the long-term average of around 2 events per year. The three driest years since 1900 were 1967, 1982 and 2006. Over these three years only 1967 had an event occurring and this was on the 24-hour period ending 2300 UTC 29 June 1967 when an ECL dumped up to 148.6 mm in southwest Gippsland. So even in extremely dry years very heavy rainfall event can occur somewhere in Victoria.

### Monthly Occurrences of strong Victorian impacts

The 319 events broken up into monthly occurrences were as follows with the 103 events following the Climate Shift in red:

January 26 (6); February 33 (5); March 26 (4); April 27 (9); May 16 (4); June 36 (12); July 22 (9); August 26 (9); September 27 (11); October 31 (12); November 19 (9); December 30 (13). The largest number occurred during June and these were dominated by ECLs events. Cool season months April to October numbered 185 while warm seasons had 134 events. There were also large numbers of events during October with less ECL event with more events occurring around the Northeast Alps. This would indicate that snow melt was playing a role during the October events. Large number of events also occurred in February and December where tropical interaction events dominated. Following the climate shift there were 66 cool season events and 37 warm season events.

The number of April to October events fell following the Shift from 0.94 events per year before the Shift and 0.64 events per year following the shift. In the active positive SOI burst of 26 events from May 2007 to January 2014 half occurred during April to October, that is at the rate of 1.6 cool season events per year. Therefore, these bursts of sustained positive SOI periods can produce large numbers of cool season events.

## 6. Examples of Synoptic Patterns Using Maximum Impact Events

### 28 November -1 December 1934 Intense low developed Bass Strait

This low (see Figure 2) rapidly intensified as it moved from west of King Island to a 982 hPa low just off the Gippsland Coast at 2300 UTC 29 November 1934 and then moved slowly towards the south southeast while



DOI: https://doi.org/10.30564/jgr.v4i3.3204

weakening slowly. There was a tropical influence in this development with an extensive area of northerly winds flowing down to Victoria at 2300 UTC 27 November 1934. Then a tropical low developed over Southwest Queensland by 2300 UTC 28 December 1934 before interacting with the King Island low.

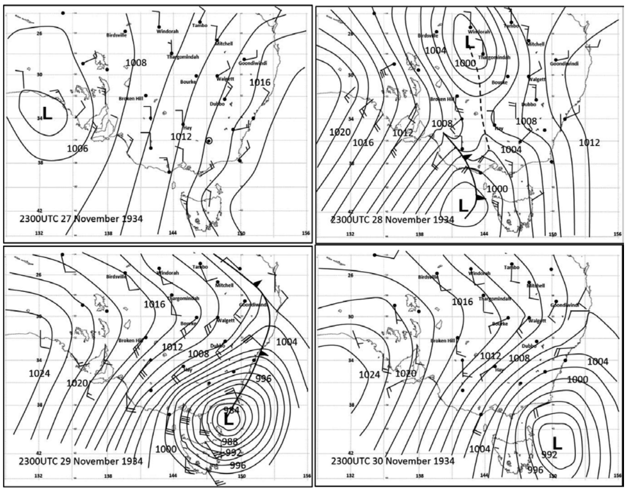


**Figure 2.** Mean sea level pressure distribution (hPa) with surface average wind observations (normal plotting convention) for 2300 UTC 27 November 1934 (top left), 2300 UTC 28 November 1934 (top right), 2300 UTC 29 November 1934 (lower left) and 2300 UTC 30 November 1934 (lower right)

Rainfall totals of 144 mm fell in Melbourne from 0900 UTC 29 November 1934 to 1630 UTC 30 November 1934. In the higher reaches of the Yarra River an average rainfall of 224.7 mm fell between 0700 UTC 29 November and 1100 UTC 1 December causing the Yarra River to rise to the record heights. In these upper regions east of Melbourne totals exceeded 350 mm within 48 hours. The top 24 hour rainfall totals were at Hazel Park 44 km south of Morwell with 266.7 mm and Sherbrooke 24 km north-northeast of Cranbourne 264.9 mm. At the Johnstone Street Bridge Collingwood around 1100 UTC Saturday 1 December the Yarra River was 39 ft. 7 in. (12.05 metres) above summer level the highest since 1891 when it reached 41 feet (12.50 metres) above summer level on Monday 13 July 1891.

There were very high ARIs associated with this event (Bunyip River ARI >150 years and ARI 100 years for the LaTrobe River, Yarra River and Yea Rivers. The SS Coramba sunk off Phillip Island and the crew of seventeen lives were lost. The severe overland flooding resulted in 20 people drowning. A party of fishermen from Lakes Entrance, with police, rowed for miles in swiftly flowing, debris-filled water in the Moe and Trafalgar districts, and saved many lives. Disastrous flooding was widespread over the Yarra Valley, South Gippsland, and the Latrobe River District, with major stock, crops and property losses. The damage was exacerbated by the gale force winds that accompanied the rain, causing heavy livestock losses through exposure, as well as much property damage. Very many trees were uprooted by the combination of high winds and sodden ground. Six thousand people were left homeless, and in Melbourne some 400 houses and factories were flooded. More than 2,500 people were rendered homeless at Mordialloc, Edithvale, Chelsea and Carrum.

## February 2005 Low

This low (Figure 3 top left) intensified to 985 hPa as it moved south down into Gippsland by 1000 UTC 2 February 2005 with the centre to the east of Bairnsdale and a secondary low forming near Hogan Island where storm force winds were reported. A series of trough lines marked by wind changes were denoted by dashed lines however they were no temperature or moisture discontinuities across these features. Heavy rain had fallen in the Melbourne area with the highest reports over the previous 12 hours were east of the City with 63 mm at Ferny Creek and 52 mm at Scoresby. The heaviest 12-hour totals in the synoptic weather stations were over Gippsland with 84 mm at Mount Nowa Nowa, 83 mm at Mount Moornapa, 80 mm at Mount Baw Baw, 60 mm at Bairnsdale and 57 mm at Orbost. Gales were indicated at Aireys Inlet, Point Wilson and Fawkner Beacon (over the Northern Bay near Melbourne).

By 1600 UTC 2 February 2005 the northern low moved west to Mount Baw Baw (top right frame Figure 3) while the low near Hogan Island intensified with winds their reaching hurricane force. Gales extended further north to Laverton. Heaviest 6-hour rainfall was 80 mm Mount Baw Baw, 76 mm Ferny Creek, 63 mm Scoresby, and 50 mm at Rhyll on Phillip Island. The trough lines still showed no temperature or moisture discontinuities across them.

At 1900 UTC 2 February 2005 (lower left frame) the northern low was near Coldstream while the southern low weakened dramatically and gales had extended northwards to Tullamarine. The trough through the Bay gained more frontal characteristics with generally warmer and moister conditions in the south to southeasterly flow to its east. Then by 2200 UTC 2 February 2005 (lower frame) the front had largely passed through Melbourne and the rain stopped (Melbourne City rainfall ceased at 2100 UTC 2 February 2005). Heavy rain and gales continued west of the front but east of the front the pressure gradient and winds eased.

For information on terrain see www.bom.gov.au/australia/radar/info/vic_info.shtml#melbourne02

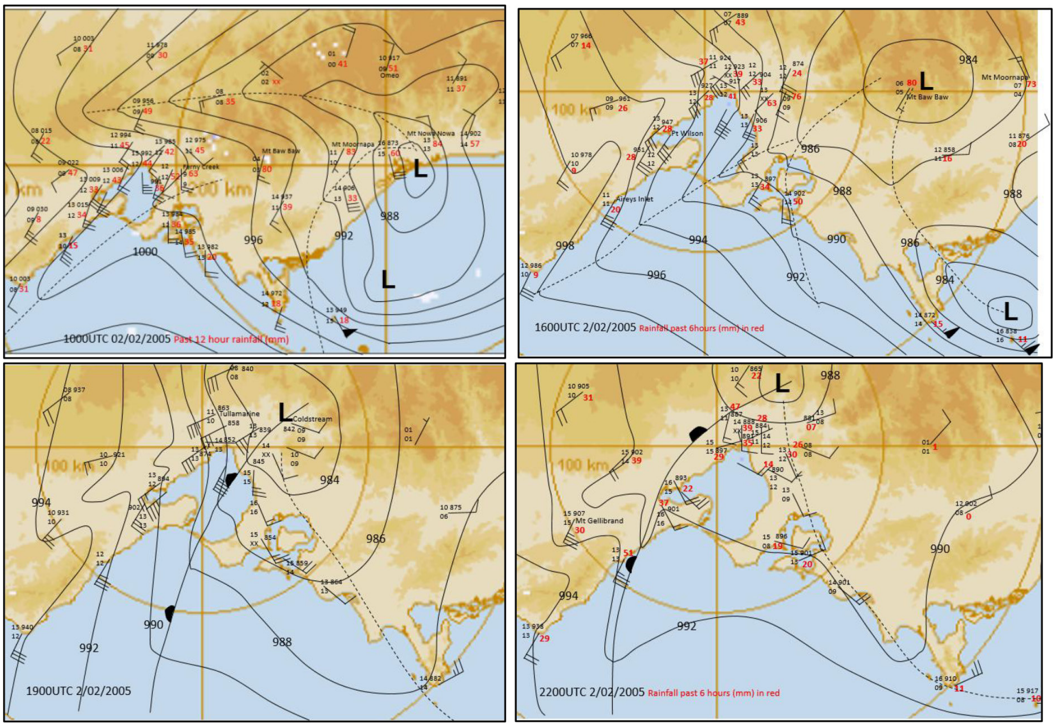


**Figure 3.** Mean sea level pressure distribution (hPa) with surface average wind observations for 1000 UTC 2 February 2005 (top left), 1600 UTC 2 February 2005 (top right), 1900 UTC 2 February 2005 (lower left) and 2200 UTC 2 February 2005 (lower right). Past rainfall totals are indicated in red.

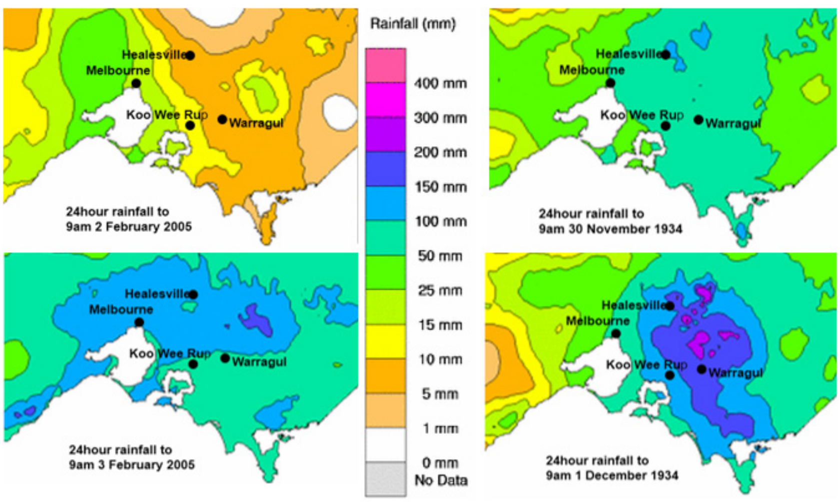


**Figure 4.** Twenty-four-hour rainfall (mm) to 2300 UTC 1 February 2005 (9 am 2nd local time and top left frame), 2300 UTC 30 November 1934 (9 am 31st local time and top right frame), 2300 UTC 2 February 2005 (9 am 3rd local time and lower left frame) and 2300 UTC 31 November 1934 (9 am 1st December local time and lower right frame).

Severe wind gusts caused extensive building damage in Melbourne and over 7,000 requests for assistance were received. Rainfall through the Melbourne area exceeded 100mm with an all-time 24-hour record for Melbourne CBD set at 120.2 mm (previous record 108 mm). Widespread riverine flooding occurred across the Port Phillip and Westernport Region. The damage from the low in New South Wales, Victoria and Tasmania reached $304 million 2011 AUD.

The Yarra River at Collingwood broke its banks for the first time since 1934. In Melbourne, major flooding was also experienced along the Dandenong and Kororoit Creeks. The Tanjil River at Tanjil Junction and Sunday Creek at Tallarook also experienced major flooding.

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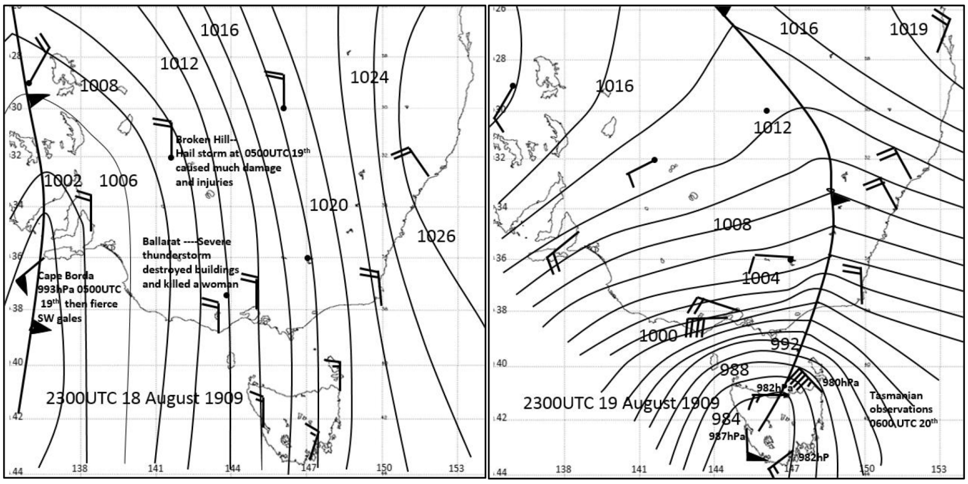


**Figure 5.** Mean sea level pressure distribution with surface average wind observations (normal plotting convention) for 2300 UTC 18 August 1909 (left) and, 2300 UTC 19 August 1909 (right).

## Comparison of rainfall between the 1934 and 2005 events

Figure 4 details the rainfall distribution between the two events with the 2005 events moving west while the 1934 event moved slowly east. Consequently in 2005 the rain was concentrated more over the Melbourne area and to the west while in 1934 a band of extreme rainfall was focussed on a region from the Upper Yarra Valley (around Healesville) down to the south-southeast over South Gippsland.

## 19-20 August 1909 Western Districts

A 1000 hPa low south of Kangaroo Island moved towards southeast and intensified to below 985 hPa over SW Tasmania (see Figure 5). The mean sea level pattern before the rapid cyclogenesis (left panel) shows tropical northerly air flowing around the eastern flank of a developing low.

There were large major flood ARIs as follows- Loddon River Laanecoorie ARI 100 years, largest on record, Loddon River Bridgewater ARI 100 years, Loddon River Serpentine, Kerang & Charlton ARI 100 years. Major flood Yarrowee River Ballarat which was the highest flood levels on record.

There was a major flood Wimmera River at Horsham, Glenorchy, Dimboola and Jeparit 100 with ARI 100 years. There were 6 fatalities associated with this event.

The Laancoorie Weir on the Loddon River on Friday 20th gave way surging water down the river Valley and bridges were swept out of sight. The town of Bridgewater was almost inundated, and the inhabitants were rescued in boats brought from Bendigo. A storm swept over Ballarat. In a quarter of an hour there was loss of life; houses were levelled, and roofs carried away; chimneys collapsed; outbuildings and fences were whirled into the streets and home furnishings were saturated. A woman was killed by lightning and another was killed when a chimney collapsed on her. A man was drowned at Learmonth (NW of Ballarat) while crossing a creek when a flash flood came down the creek. Another man was drowned in the district from flash floods.

The heaviest 24 hour rainfall were at Daylesford, 35 km NE of Ballarat 29.2 mm 19th and 87.4 mm 20th, at Lyonville 39 km ENE of Ballarat 35.8 mm 19th and 100.1 mm 20th and at Avoca 23 km W of Maryborough, 30.2 mm 19th and 85.1 mm 20th.

To explain surface conditions in Victoria leading into the August rain, June was exceptionally wet, seeing in many places (e.g. Melbourne) a record number of rainy days for any month. The heavy June falls had already made the ground throughout Victoria very moist, and even though July rainfall was only above normal in the north of the State was of relatively little significance as evaporation was too low to dry the ground. There were heavy 24 hour falls in the Wimmera on 9 August 1909 (to 41.1 mm) and the third of four major depressions for the month arrived in western Victoria on the 17 August 1909. This produced very heavy falls upon already-saturated catchments on flat land where water was not draining away quickly. As the slow-moving depression linked with warm air from the Tasman Sea thunderstorms began to develop over the Wimmera region on the 18 August 1909.

## West Coast of Victoria March 1946 heaviest rainfall in nearly 150 years.

A tropical low developed in southwest QLD by 2300 UTC 14 March 1946 (Figure 6) and interacted with a low

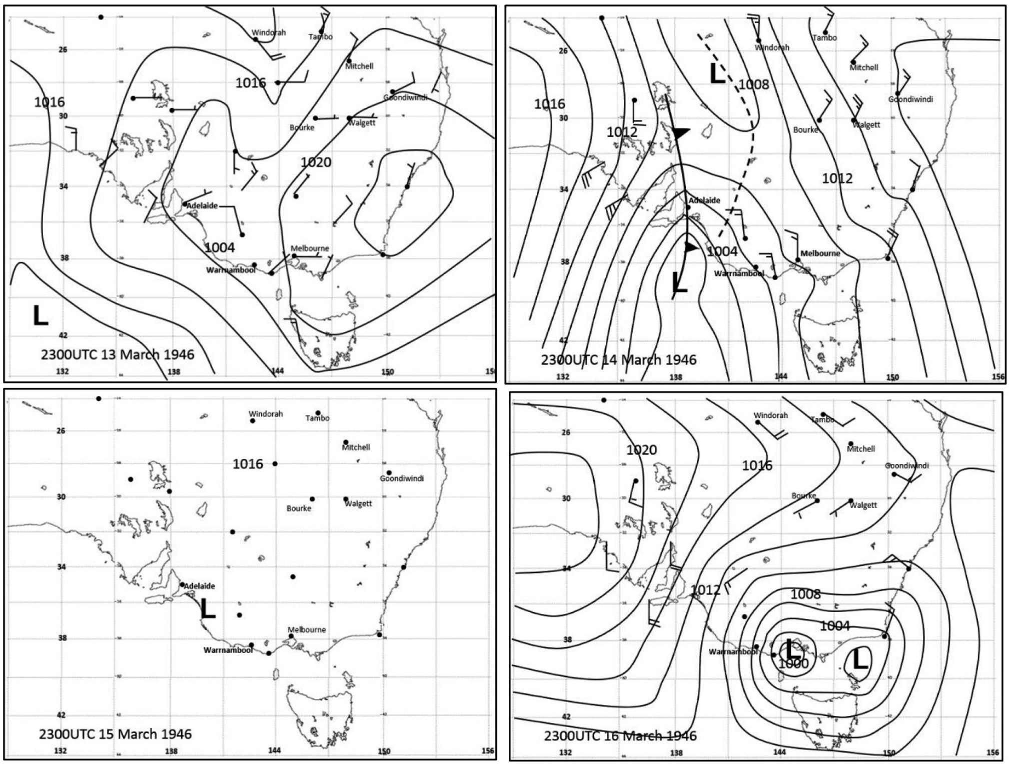


**Figure 6.** Mean sea level pressure distribution (hPa) surface average wind observations (normal plotting convention) for 2300 UTC 13 March 1946 (top left), 2300 UTC 14 March 1946 (top right), 2300 UTC 16 March 1946 (lower right) and for 2300 UTC 15 March 1946 (lower left) as there was no chart available just the position of the low.

near Mt Gambier to form a 998 hPa low near Melbourne on 2300 UTC 16 March 1946. From reports the heaviest rain (200 mm) fell in the Hamilton District from 2300 UTC 14 March 1946 to 0700 UTC 17 March 1946 while this interaction was underway. There were Seven Fatalities with major flooding in the Glenelg River at Casterton (ARI 100 years). Major damages occurred in all Western districts with various bridges washed away. The major flood in the Merri River at Warrnambool had an ARI greater than 100 years. The Moyne River at Port Fairy and Portland also had an ARI greater than 100 years. The floods which covered the western district and southern Wimmera from Natimuk to the sea and as far east as Mortlake. Scores of people were evacuated in Hamilton, Portland, Port Fairy, Warrnambool, Casterton, Heywood, Branxholme, Macarthur, and other towns.

Thousands of head of valuable stock perished. Scores of bridges were submerged or swept away, roads and railways washed out in many places, and telephone lines brought down.

•Record 24hour rainfall

Branxholme 77.0 mm 17th 173.5 mm 18th All-time record 1883 to present; Hawksdale 34.0 mm 16th 158.2 mm 17th record 1944 to 1995 42.2 mm 18th; Koroit 45.2 mm 16th 201.9 mm 17th since 1889 record. Port Fairy 189.7 mm 17th record since 1884.

Warrnambool 59.7 mm 16th 167.1 mm 17th record since 1867.

Yambuk -62.2 mm 16th 181.9 mm 17th record.

## Recent Comparison Events to March 1946 in December 2008 and January 2011.

Two recent events are presented below to compare with the record 1946 event and in the next section the wind structures of these two events are presented. These structures are similar, but the heaviest rain was associated with the 2011 event where tropical air found its way right down to Victoria. This illustrates the probable structure of the 1946 event given it had a tropical inflow associated with it.

### Low December 2008 (see Figure 7)

A 990 hPa low over Western Victoria intensified and formed a 983 hPa East Coast Low near Eden 13-14 Dec 2008. In this event the State Emergency Service, responded to more than 900 calls for help, mostly to remove fallen trees. Long term 24 h rainfall records for December were broken in Western Victoria on 13 December 2008 --Cavendish PO 65.0 mm 124 years of data; Nelson 69.4 mm 121 years; Merino 74.6 mm 117 years ; Branxholme

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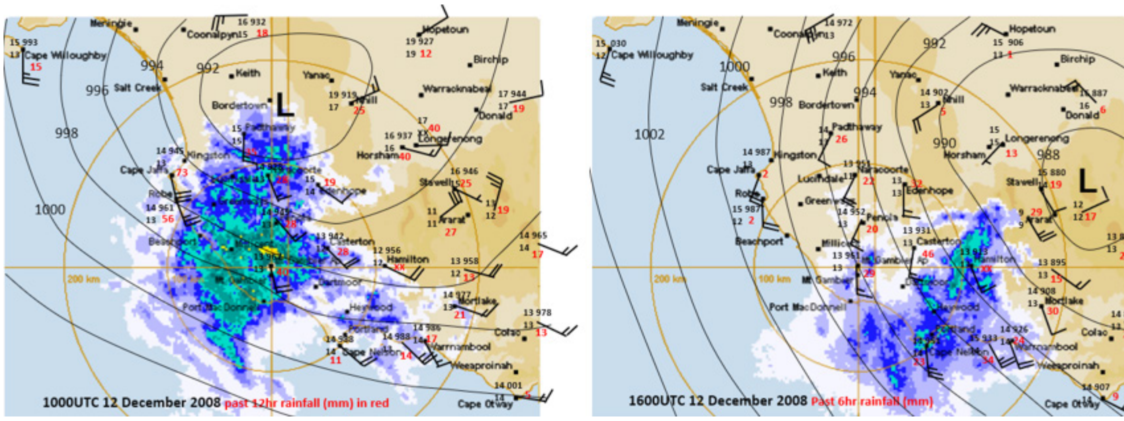


**Figure 7.** Mean sea level pressure distribution (hPa) during heaviest rainfall showing average wind plots, surface temperature and dew points in Celsius overlaid on Mt Gambier radar imagery with 100km range rings for 1000UTC 12 December 2008 (left with 12hour past rainfall in red) and 1600UTC 12 December 2008 (right with past 6-hour rainfall).

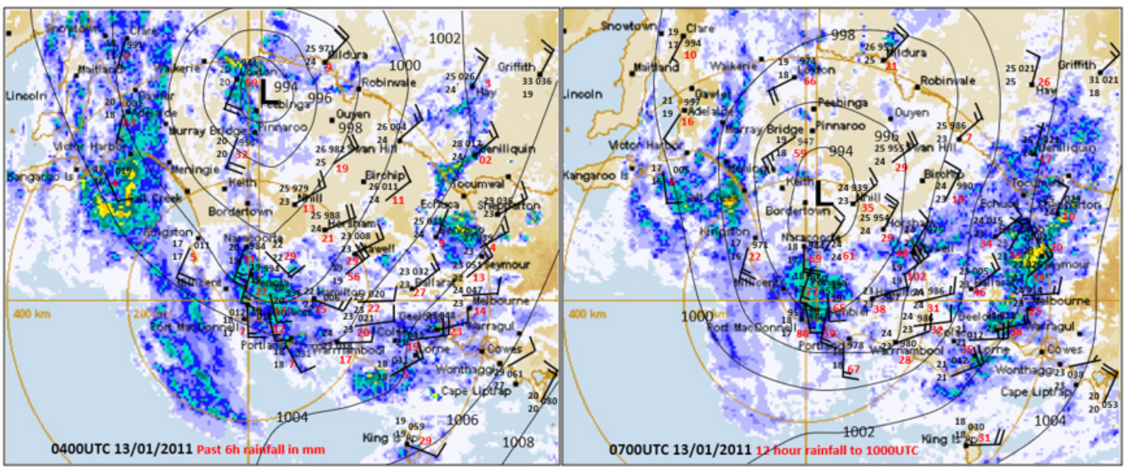


**Figure 8.** Mean sea level pressure distribution (hPa) during heaviest rainfall showing average wind plots, surface temperature and dew points in Celsius overlaid on Mt Gambier radar imagery with 200 km range rings for 0400 UTC 13 January 2011 (left with 6hour past rainfall in red) and 0700 UTC 13 January 2011 (right with past 12-hour rainfall).

87 mm 105 years; Penshurst 76.0 mm 72 years ; Casterton Showgrounds 86.0 mm 53 years; Strathdownie 85.5 13 47.2 1986 46years. Port Fairy 70.8 mm since 1898; 89.6 mm Benwerrin.

## January 2011 Low with tropical inflow (see Figure 8)

11-12 January 2011 a 999hPa low developed near Portland moved SW on 13 January before intensifying to a 987 hPa low SW of Tasmania on 14 Jan 2011 with extraordinary tropical moisture advection down to VIC from the weather system causing the Brisbane Floods. A record flood peak hit the town of Rochester in Victoria. The Campaspe River near Rochester reached an historic peak of 9.12 metres - exceeding 1956 levels – and split the town in two. An evacuation warning was issued for Rochester's entire population of about 3,000 people. The major regional centres of Echuca, Kerang, Charlton and Horsham were also affected. The rainfall across the state between 9 am Thursday 13th and 9am Friday 14th was amongst the highest for the event and the most record breaking statewide. More than one-third of Victoria recorded rainfall totals in excess of 40 mm, which is approximately the equivalent of doubling the long-term average for January in this area. 25 stations recorded their highest ever daily rainfall for January during this 24-hour period, including the station at Maryborough which opened in 1878. 15 stations recorded rainfall totals in excess of 80 mm, with Mount William in the Grampians recording 132.8 mm and Nelson observing 113.2 mm.

In Figure 8 a 992 hPa low south west of Mildura at 0400 UTC moved down to south-western Victoria by 0700 UTC 13 January 2011. Moist tropical air (dewpoints well above 20 $^{0}$C) was directed into Victoria around the

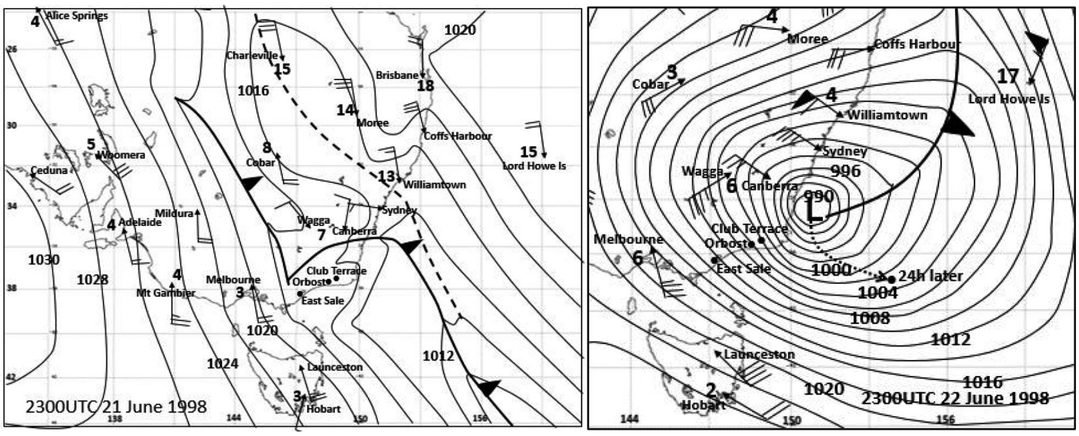


**Figure 9.** Mean sea level pressure distribution (hPa) showing gradient level winds (mostly at 900 metres elevation) and surface dewpoints for 2300 UTC 21 June 1998 (left) and for 2300 UTC 22 June 1998 (right).

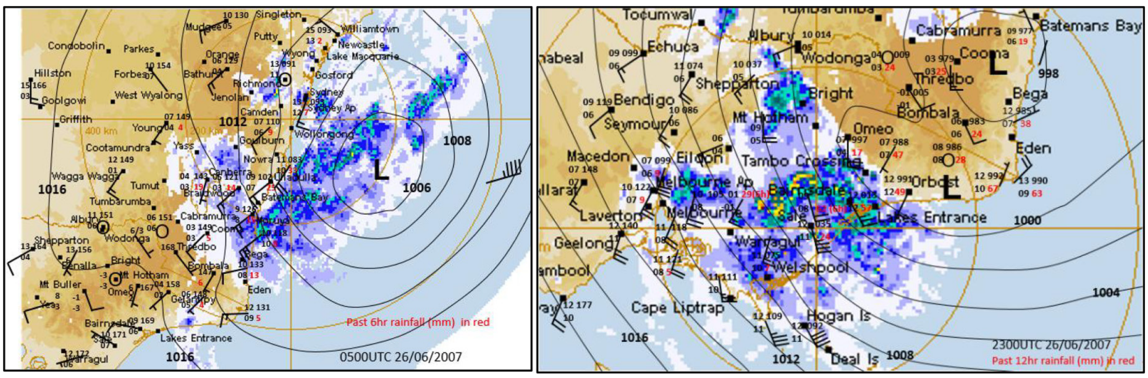


**Figure 10.** Mean sea level pressure distribution (hPa) during heaviest rainfall showing average wind plots, surface temperature and dew points in Celsius for 0500 UTC 26 June 2007 (left) and for 2300 UTC 26 June 2007 (right).

eastern side of the low. This covers a period of very heavy rainfall for example The Grampians (Mount William) recorded 102.0 mm in the 12 hours to 1000 UTC 13 January 2011. The Insurance Council of Australia damage statistic for this event was $(2011)126,495,000.

## Gippsland ECLs 22-23 June 1998 (see Figure 9)

Extremely rapid development of an East Coast Low along the Far South Coasty of New South Wales.

In East Gippsland more than 1000 houses were flooded, at least 12 bridges were swept away. Club Terrace Post Office recorded 284.6 mm of rain in 24 hours, the heaviest daily total for rain ever officially recorded in East Gippsland. In Orbost 247.6 mm was recorded in the 24 hours to 9 am 24th June 1998 which was an all-time daily record since 1883.

The heaviest rain fell just after the sequence in the Figure above - In the head waters of the Mitchell River, which flows through between Sale and Orbost, 145 mm was recorded between 2300 UTC 22 June and 0500 UTC 23 June at both Crooked River and Waterford. In the Snowy River 220 mm was recorded at Basin Creek and 182 at Buchan between 2300 UTC 22 June and 1100 UTC 23 June 1998. In the Cann River Rockton in the headwaters recorded 125 mm also between 2300 UTC 22 June and 1100 UTC 23 June 1998.

## Gippsland ECLs 26-27 June 2007 (see Figure 10)

The low in Figure 10 crossed the coast at Gabo Island (southeast tip of the Australian continent) around 1400 UTC 26 June 2007 - Gabo Island at 1100 UTC had and average wind of 230/29 knots and a bar of 1005 hPa. Then at 1700 UTC 040/23 knots 996.1 hPa with 58.0 mm in the 6 hr to 1700 UTC.The rain then developed over West Gippsland (see right frame Figure 10).

There were extreme rainfalls over eastern Victoria; Mt Wellington and Reeves Knob had 377 mm and 321 mm respectively.

•Mt Wellington recorded 319 mm of rain on the 28th June which is a Victorian state record for June and was the second highest in Victoria for any month. Another 9 stations with 25 or more years of record and 5 stations with

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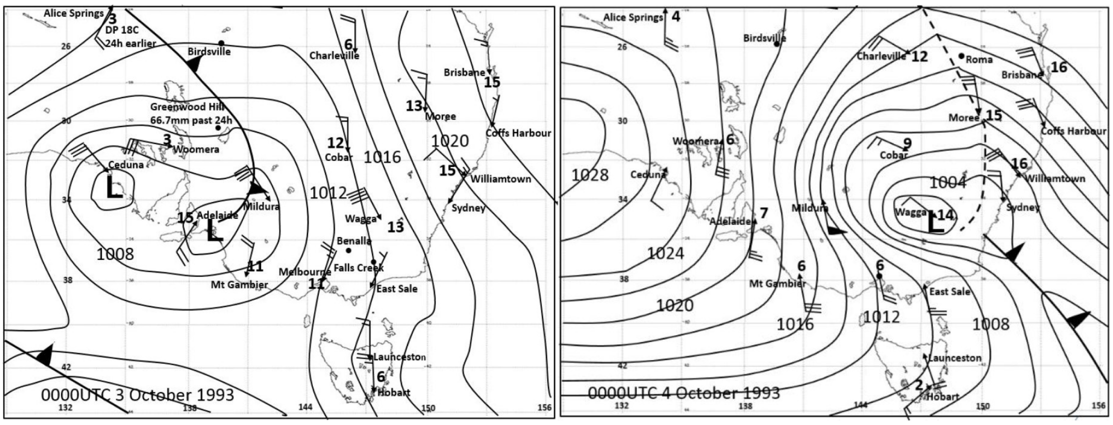


**Figure 11.** Mean sea level pressure distribution (hPa) showing gradient level winds (mostly at 600metres elevation) and surface dewpoints for 0000 UTC 3 October 1993 (left) and for 0000 UTC 4 October 1993 (right).

50 or more years of record set new records for the highest June daily rainfall. Most catchments in the Gippsland area were already saturated due to rain in the previous week. In West Gippsland the Traralgon creek catchment experienced major flooding.

•The Snowy river catchment experienced moderate to major flooding.

•Major Flood Macalister River Glenmaggie ARI 100 years Largest on record.

•Major Flood Thomson River Cowwarr ARI 25 years

•Major Flood Avon River The Channel ARI 40 years Stratford peaked around 8.9 metres.

•Major Flood Mitchell River Glenaladale peaked around 8.22 metres ARI 50years

•Major Flood Gippsland Lakes Entrance ARI 20 years

## Victorian Alps October 1993 Low with tropical inflow (see Figure 11)

The extreme rainfall fell ahead of the cold front trough seen crossing Southeast Australia in Figure 11.

This occurred in a region of large-scale ascent as exemplified by the warm air advection wind profiles there as indicated by the Melbourne and Wagga upper winds as shown below. The pattern in the left frame is associated with heavy rain over Northern Victoria with air from the tropics flowing down to Victoria east of the low over South Australia.

Extreme rainfall on 3 - 4 October 1993 in catchments caused twelve mountain-fed rivers to flood on both the NE and SE sides of the Victorian Alps. Heavy damage occurred in NE Victoria where about 4,000 people were evacuated mainly at the towns and surrounding farms of Benalla (1,500+ evacuated), Shepparton, Myrtleford, Wangaratta and Euroa. Over 1000 people had to be temporarily housed in emergency centres. These figures are indicative of the large number of damaged homes and shops, some flooded by over a metre of water. The following are the larger ARIs experienced on some of the Victorian river systems affected:

Ovens at Bright and Myrtleford (1 in 100) and at Wangaratta (1 in 120); Broken River at Benalla (1 in 100); Broken Creek at Nathalia (1 in 100); Many roads and bridges were damaged, some destroyed. Thousands of kilometres of fencing were damaged. More than 3,500 sheep and 1,600 cattle died while crops, orchards and market gardens were destroyed, and huge dairy and other primary production losses resulted. There were also serious losses in Gippsland. The total estimated cost to Victoria was approximately \$350 m. (One death was reported at Loxton, SA, due to downstream flooding on the Murray River). The heaviest 24hour rainfalls reported were: - Molyullah 14 km ESE of Benalla 189.0 mm 4$^{th}$ Edi Upper 234.4 mm 4$^{th}$- Falls Creek 275.0 mm 5$^{th}$ -Mount Buffalo 212.0 mm 4$^{th}$.

## Overland flooding in Melbourne from extensive thunderstorms 2 December 2003 (Figure 12)

Overnight from the 2nd to the 3rd December 2003 severe thunderstorms formed near Craigieburn around midnight. Heavy rainfall was recorded in the northeast suburbs of Melbourne with the largest falls being 108 mm at Viewbank (Automatic Weather Station) 107 mm at Merri Creek Bell St, 106.6 mm at Eastern Golf Club, 104.6 mm at Banksia St Heidelberg, 99.8 mm at the Eastern Freeway, 88.4 mm at Gardiner Creek, 87 mm at Northcote and 78.2 mm at Lower Plenty. This rainfall caused flooding in many northeast suburbs and most of it occurred within a one to two-hour period around 1500 UTC 2 December 2003.

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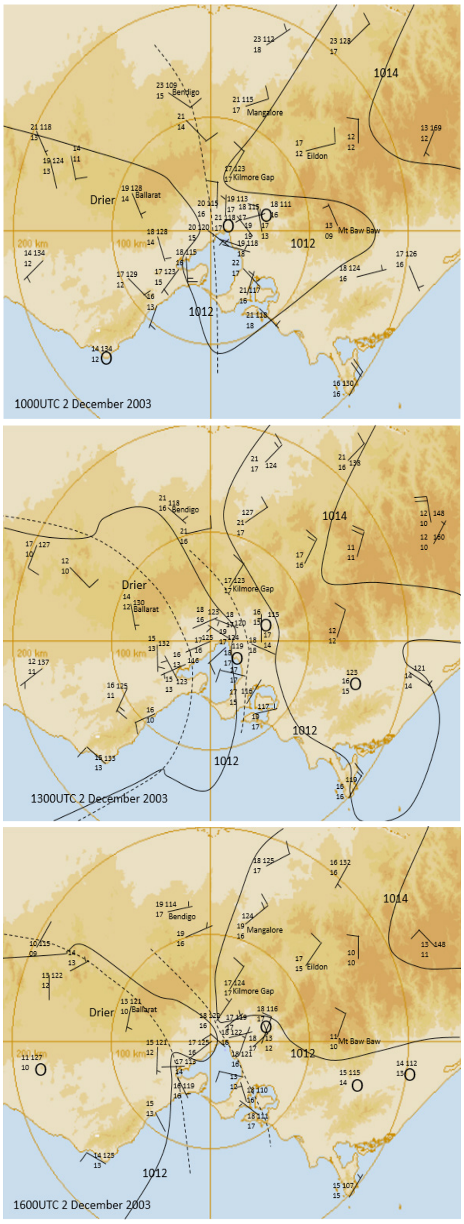


**Figure 12.** Mean sea level pressure distribution (hPa) showing average surface winds, surface temperatures and dewpoints for 1000 UTC 2 December 2003 (top left), 1300 UTC 2 December 2003 (top right) and for 1600 UTC 2 December 2003 (lower left).

At Viewbank Automatic Weather Station (AWS) 27.0 mm was recorded in 14 min to 1439 UTC 2 December 2003, 24.0 mm in 39 min to 1530 UTC and 76.2 mm was recorded between 1425 UTC and 1530 UTC 2 December 2003. Radio reports at the time suggested that the heaviest rain was in the Preston to Northcote area which is 8km west of Viewbank. The Melbourne CBD registered 32.2 mm in the 1 hour to 1430 UTC 2 December 2003. The hourly rainfall rates were consistent with an ARI 100-year event. Hail to 2.5 cm diameter was reported at Fairfield during the early morning.

## Overland flooding in Melbourne from extensive thunderstorms 29 December 2016 (Figure 13) with strong tropical inflow

Figure 13 shows a trough (dashed line) south west of Melbourne with general northerly to northeasterly winds to its east. The stations displaying these winds have dewpoints of 22$^0$C to 24$^0$C (except for mountain stations) indicating their tropical origins.

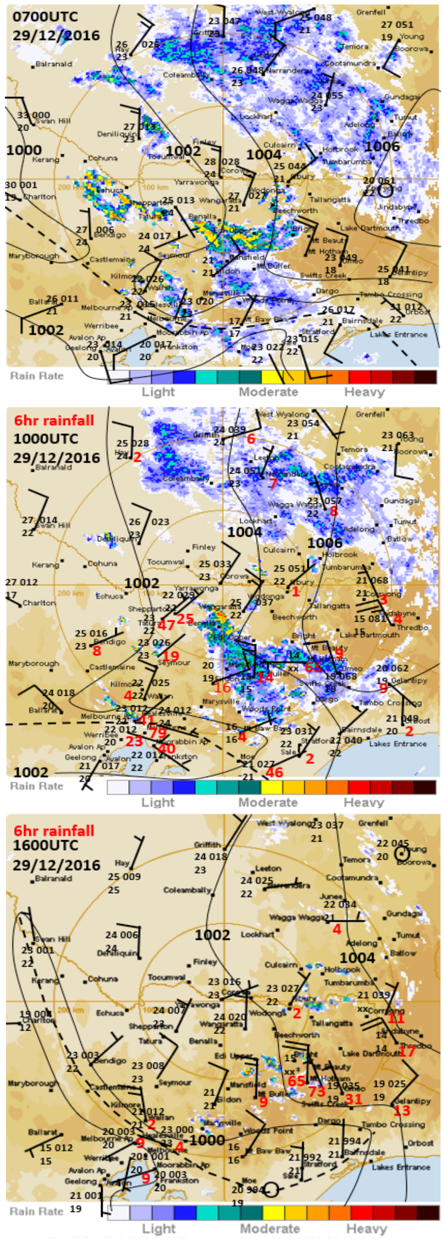


**Figure 13.** Mean sea level pressure distribution (hPa) showing average surface winds, surface temperatures and dewpoints overlaid on Yarrawonga radar with 100 km range rings for 0700 UTC 29 December 2016 (top left), 1000 UTC 29 December 2016 with past 6 hour rainfall (top right) and for 1600 UTC 29 December 2016 with past 6 hour rainfall (lower left).



DOI: https://doi.org/10.30564/jgr.v4i3.3204

Severe thunderstorms moved from the NW across the whole Melbourne metro area during the afternoon peak. 40 to over 70 mm was recorded frequently in around 30 minutes producing widespread flash flooding. Roads and expressways rapidly became impassable, including the Western Ring Road and Tullamarine Freeway while rail services were delayed or suspended, and trams delayed by deep water. The highest short-duration rainfalls during this storm were at Viewbank, in the north-eastern suburbs of Melbourne, where 40.2 millimetres fell in 15 minutes between 3.07 and 3.22 p.m. 29/12/2016.This is amongst the heaviest known rainfalls for such a duration in Victoria (Table 2) This rainfall rate surpassed the 1% annual exceedance probability rainfall. Indicative of the tropical influence Melbourne equalled its highest dewpoint on record for any month. The December 2016 event had a slightly higher peak dewpoint (24.0 °C) than those recorded on 13 January 2011 (23.9 °C) or 4 February 2011 (23.2 °C), although the very high dewpoints were sustained over a longer period in the two 2011 events.

### Overland flooding in Melbourne from extensive thunderstorms February 2011 A trough with tropical inflow (see Figure 14)

During 4-5 of February 2011 high levels of moisture associated with ex-Tropical Cyclones Yasi and Anthony fed into a slow-moving surface low pressure trough extended from central Australia, through NW VIC and Melbourne. The dotted line in Figure 14 shows the location of the trough and its movement towards Melbourne. Tropical air is indicated northeast of the trough lone by dewpoints reaching $24^0$C to $25^0$C.

Major floods many stream & widespread flash flooding resulted. The persistence of the trough provided conditions that allowed thunderstorms to develop one after the other, affecting large areas of Victoria (SES received in the order of 6000 requests for assistance). The south-eastern suburbs of Melbourne saw repeated thunderstorms, resulting in total rainfall in excess of 150 mm at some locations. Widespread flash-flooding was reported around the Metropolitan area. Numerous stations recorded their highest daily rainfall for February. The heavy rain fell on catchments already saturated by the December and January rain events leading to widespread riverine flooding. Major flood warnings were issued for the Bunyip River, Dandenong Creek and Sunday Creek. A mean sea level sequence in Figure 1 shows a trough through southwest Victoria with moist tropical air (dewpoints above $20^0$C) flowing in from the north moved eastward through Melbourne. During the sequence in Figure 1 some of the heaviest rain was recorded in Melbourne

For example, Moorabbin recorded 48.2 mm in 1 hour to 0730 UTC 4 February 2011; 24.2 mm in 1 hour to 0900 UTC 4 February and 82.0 mm in 4 hours to 1000 UTC 4 February. The Insurance Council of Australia damage statistics for this event was $(2011 AUD) 487,615,000.

### March 2011 Un-Official 24 hr rainfall Event (see Figure 15)

This event was not considered a major flood event as the only major flooding was recorded in the Snowy River catchment, driven by rainfall in NSW. The extreme rainfall was much more isolated causing flash overland flooding.

This record was 377.8 mm at Tidal River (Elevation 15 metres) in the 24 hours to 2300 UTC 22 March 2011 and

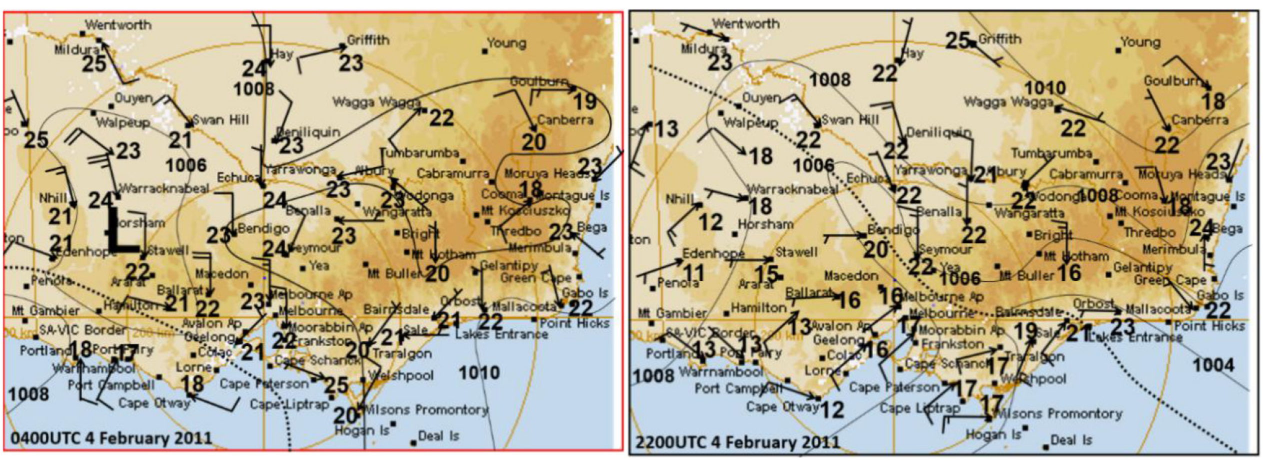


**Figure 14.** Mean sea level pressure distribution (hPa) with surface average wind observations (normal plotting convention) and dewpoints (degrees Celsius) dotted line marks trough position for 0400 UTC 4 February 2011(top left), 1100 UTC 4 February 2011 (top right) and 2200 UTC 4 February 2011 (lower left).

 DOI: https://doi.org/10.30564/jgr.v4i3.3204

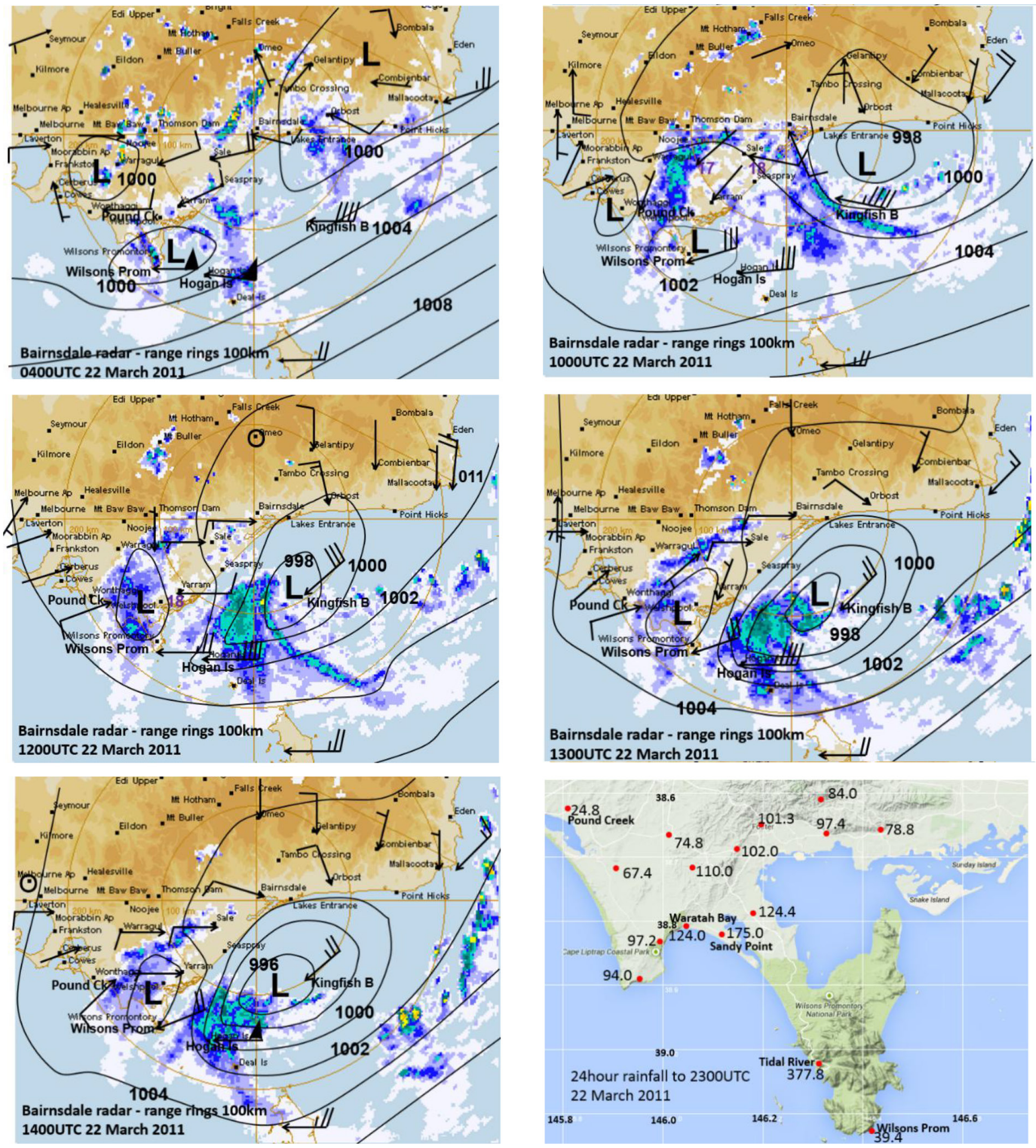


**Figure 15.** Mean sea level pressure distribution (hPa) together with average surface wind observations (normal plotting convention) overlaid on Bairnsdale radar images for 0400 UTC 22 March 2011(top left), 1000 UTC 22 March 2011(top right), 1200 UTC 22 March 2011 (centre left), 1300 UTC 22 March 2011 (centre right), 1400 UTC 22 March 2011 (lower left) and in the lower right frame the 24 h rainfall totals in the Wilsons Promontory region to 2300 UTC 22 March 2011.

this at the time was an un-official Bureau of Meteorology rain gauge. The is not generally a heavy rainfall site as the second highest daily total listed is 122.2 mm in 24 hours to 2300 UTC 27th August 1973 which was another isolated heavy fall observation associated with an ECL and not included in current list of events.

The heaviest rainfall from radar began at Tidal River about 0800UTC 22 March and was gone by 1700 UTC 22 March. Pound Creek and Wilsons Promontory Automatic Weather Stations received much lighter rainfall over the 24 hours 24.8 mm and 39.4 mm respectively. From the MSL sequence below in Figure 15 the main low near Kingfish B had heavy rain associated with it but this remained over water. The secondary low which formed near Pound Creek then became anchored between Pound Creek and Wilsons Promontory with all the heavy rain between those two stations. In the lower right frame, the rainfall distribution shows the largest rainfall reports in that area. During the heavy rainfall the dewpoint at Wilsons Promontory was 18 degrees Celsius indicating a relatively

  DOI: https://doi.org/10.30564/jgr.v4i3.3204

warm moist environment.

The rainfall occurred in an area where NCEP/NCAR reanalyses indicated there was large scale warm air advection at low to middle levels. The reanalyses however did not resolve the complex mesoscale lows in Bass Strait near Wilsons Promontory.

## 7. Examples of Turning Winds with Height during Major Events

There is limited radiosonde coverage in the heavy rainfall areas of Victoria in the Northeast and in recent years in Gippsland, however there is sufficient data available for some of the big impact events shown below to suggest a strong relationship between anticyclonic turning of the winds and extreme rainfall as shown for many parts of the globe. This investigation adds to a series of papers which related the turning of the winds anticyclonically with height in the lower to middle troposphere with extreme rainfall [19-25].

See examples below:

### April 1977

Flash Flooding and Victorian Rainfall Records as follows at Laverton rain commenced around 0515 UTC 7 Apr 1977 and following recorded 137 mm in 3 h 137 mm at 153 mm in 4 h; In Northern Melbourne suburbs at Wollert 7 Apr 1977 191 mm in 12h; Mt Ridley 7 Apr 1977 193 mm in 12 h 192 mm and in the Southeast at Bentleigh East 7 Apr 1977 203 mm in 12 h.

Laverton winds 1700 UTC 6 April 1977 850 hPa 135/6.18 m/s; 700 hPa 020/10.30 m/s; 500 hPa 335/29.86 m/s.

Laverton winds 2300 UTC 6 April 1977 914 metres 135/18.02 m/s; 2133 metres 100/12.36 m/s; 3657 metres 095/7.2 m/s; 5486 metres 19.56 m/s.

Laverton winds 2300 UTC 7 April 1977 850 hPa 190/18.53 m/s; 700 hPa 185/19.56 m/s; 500 hPa 175/25.74 m/s.

### March 1983

There were no major floods as the event followed a long drought period. Tanybryn (elevation 402 metres) in the 24 hours to 2300 UTC 21 Mar 1983 recorded 375.0 mm of rain (a record). This occurred as a large tropical low caused widespread heavy rain through Victoria with Madalya in West Gippsland recording 239.0 mm in the 24 hours to 2300 UTC 21 March 1983 which was a record (data from 1900). The record rainfall period was characterised by strong southeasterly flow onto the Otway ranges as a deep tropical low moved from near Cobar to the Melbourne area. From the surrounding radiosonde data shown below these strong southeast winds had the wind structure above the surface conducive to extreme rainfall where the winds turned anticlockwise with height between the 850 hPa and 500 hPa levels.

### March 1983 Mount Gambier observations

At 0500 UTC 21 March 1983- 850 hPa 135/20.59 m/s; 700 hPa 125/18.53 m/s; 500 hPa 095/10.30 m/s.

At 1100 UTC 21 March 1983- 850 hPa.140/28.83 m/s; 700 hPa 100/16.47 m/s; 500 hPa 075/15.44 m/s.

At 1700 UTC 21 March 1983- 850 hPa 150/29.86 m/s; 700 hPa 110/8.24 m/s; 595 hPa 105/11.33 m/s.

### Launceston observations

At 2300cUTC 20 March 1983- 850 hPa 085/6.18 m/s; 700 hPa 050/7.21 m/s; 650 hPa 030/9.27 m/s.

At 0500c UTC 21 March 1983- 850 hPa 115/8.24 m/s; 700 hPa 100/11.33 m/s; 595 hPa 065/16.47 m/s.

At 1100c UTC 21 March 1983- 850 hPa 095/16.47 m/s; 700 hPa 055/13.38 m/s; 500 hPa 350/9.26 m/s.

At 1700c UTC 21 March 1983- 850 hPa 105/21.62 m/s; 700 hPa 050/19.56 m/s; 600 hPa 045/19.56 m/s

### Melbourne Observations: -

At 2300 UTC 20 March 1983- 850 hPa 110/27.8 m/s; 700 hPa 075/15.44 m/s; 500 hPa 025/13.38 m/s.

At 1100 UTC 21 March 1983- 850 hPa 075/15.44 m/s; 700 hPa 055/16.47 m/s.

### February 2005 (Synoptic pattern in Figure 4)

The Melbourne Airport upper winds during the heaviest record rainfall turned anti-cyclonic with height indicating extreme rainfall as follows.

At 1100 UTC 2 February 2005 850 hPa 190/24 m/s; 700 hPa 175/24 m/s; 500 hPa 120/20 m/s; and at Melbourne Airport 1700 UTC 2 February winds; 850 hPa 205/27.28 m/s; 700 hPa 145/24.2 m/s 630 hPa 140/31.9 m/s.

Melbourne Airport rainfall was 52.0 mm 1000 UTC to 1600 UTC 2 February 2005 and 57.4 mm 1600 UTC to 2200 UTC 2 February 2005 then heavy rain ceased as backing of the winds became confined to below 850 hPa.

### April 2004

Record 24hr rainfall West Gippsland including East Sale 108.8 mm in 24 hr to 2300 UTC 23 April 2004.

East Sale 1100 UTC 23 April 2004 850 hPa 165/4.63 m/s 700 hPa 120/5.15 m/s 500 hPa 070/15.44 m/s.

East Sale 1700 UTC 23 April 2004 850 hPa 185/26.25 m/s 700 hPa 160/20.59 m/s 500 hPa 160/22.65 m/s 400 hPa 155/19.05 m/s.

East Sale 2300UTC 23 April 2004 850 hPa 185/19.56 m/s 700 hPa 175/14.41 m/s 500 hPa 170/19.05 m/s.

**Low December 2008 (Synoptic pattern in Figure 7)**

In this event the State Emergency Service, responded to more than 900 calls for help, mostly to remove fallen trees.

Long term 24 h rainfall records for December were broken in Western Victoria on 13 December 2008 --Cavendish PO 65.0 mm 124 years of data; Nelson 69.4 mm 121 years; Merino 74.6 mm 117 years; Branxholme 87 mm 105 years; Penshurst 76.0 mm 72 years ; Casterton Showgrounds 86.0 mm 53 years; Strathdownie 85.5 13 47.2 1986 46 years. Port Fairy 70.8 mm since 1898.

Mount Gambier radiosondes 2300 UTC 11 December 2008 850 hPa 035/9.3 m/s 700 hPa 010/6.2 m/s 500 hPa 355/16.5 m/s.

Mount Gambier radiosondes 0400 UTC 12 December 2008 850 hPa 070/7.7 m/s 700 hPa 345/12.4 m/s 500 hPa 305/23.2 m/s.

**11-13 January 2011 (Synoptic pattern in Figure 8)**

The sounding at Melbourne at 0500 UTC 13 January 2011 showed the warm air advection type structure as follows 914 hPa 045/13.4 m/s; 850 hPa 025/21.1 m/s; 700hPa 025/18.5 m/s; 500 hPa 360/19.1 m/s; 400 hPa 345/22.7 m/s; and again at 1100 UTC 13 January as follows:

925 hPa 025/25.7 m/s; 850 hPa 15/32.4 m/s; 700 hPa 345/17.5 m/s; 500 hPa 335/20.6 m/s; 400 hPa 325/22.1 m/s.

The sounding at Mt Gambier at 2300 UTC 12 January 2011 also had this structure: - 925 hPa 055/5.7 m/s; 850 hPa 060/2.6/ m/s; 700 hPa 030/5.7 m/s; 500 hPa 350/27.8 m/s;0 400 hPa 345/29.9 m/s.

**Gippsland September 1993**

Major Flood Gippsland to ARI 70 years. Major Flood Maribyrnong River 53homes flooded.

Gippsland 24 hr rainfall_Madalya 149.4 mm 15$^{th}$ 105.0 mm 16$^{th}$

24 hour rainfall near Maribyrnong catchment Heskett 94.2 mm 15$^{th}$ 52.2 mm 16$^{th--}$

Laverton 2300 UTC 13 September 1993 600 metres 165/7.2 1m/s; 900 metres 155/10.30 m/s; 2100 metres 130/12.36 m/s; 3600 metres 085/10.30 m/s; 4200 metres 045/10.30 m/s; 9000 metres 130/12.6 m/s.

Laverton 1700 UTC 14 September 1993 600 metres 175/17.5 m/s; 900 metres 175/17.5 m/s; 2100 metres 165/17.5 m/s; 3600 metres 160/16.47 m/s; 4200 metres 155/16.47 m/s.

Laverton 0500 UTC 15 September 1993 600 metres 180/16.47 m/s; 900 metres 170/17.5 m/s; 2100 metres 165/14.41 m/s; 3600 metres 160/13.38 m/s; 4200 metres 150/12.36 m/s.

East Sale 1700 UTC 15 September 1893 600 metres 200/15.44 m/s; 900metres 190/15.44 m/s; 210 metres 190/12.36 m/s; 3600 metres 175/12.36 m/s 4200 metres 165/15.44 m/s.

**Gippsland June 1998 (Synoptic pattern in Figure 9)**

Record floods Gippsland and in Orbost 247.6 mm was recorded in the 24 hours to 9 am 24$^{th}$ June 1998 (record).

Laverton (Melbourne) upper winds - At 1100UTC 22 June 1998 850 hPa 135/13.90 m/s; 700 hPa 120/6.69 m/s; 500 hPa 105/4.12 m/s.

At 2300 UTC 22 June 1998 850 hPa 155/18.53 m/s; 700 hPa 160/15.96 m/s; 500 hPa 080/8.24 m/s; At 1100 UTC 23 June 1998 850 hPa 195.00 15.44 m/s; 700 hPa 185/19.56 m/s; 500 hPa 175/8.24 m/s.

East Sale at 0500 UTC 23 June 1998 850 hPa 180/23.5 m/s; 750 hPa 160/20.0 m/s.

**Gippsland June 2007 (Synoptic pattern in Figure 10)**

Major Flood Macalister River Glenmaggie ARI 100 years Largest on record.

No more East Sale winds available but Melbourne showed the anticyclonic wind turning early. Melbourne 2300 UTC 26 June 2007 850 hPa 175/25.23 m/s 700 hPa 155/26.25 m/s 500 hPa 145/22.14 m/s.

Victorian Alps October 1993 (Synoptic pattern in Figure 11)

The following are the larger ARIs experienced on some of the Victorian river systems affected:

Ovens at Bright and Myrtleford (1 in 100) and at Wangaratta (1 in 120); Broken River at Benalla (1 in 100); Broken Creek at Nathalia (1 in 100);

The extreme rainfall fell ahead of the cold front trough seen crossing Southeast Australia in Figure 5.

This occurred in a region of large-scale ascent as exemplified by the warm air advection wind profiles there as indicated by the Melbourne and Wagga upper winds as shown below.

The heaviest 24 hour rainfalls reported were: - Molyullah 14 km ESE of Benalla 189.0 mm 4$^{th}$ Edi Upper 234.4 mm 4$^{th}$- Falls Creek 275.0 mm 5$^{th}$ -Mount Buffalo 212.0 mm 4$^{th}$.

Upper winds at Laverton (Melbourne) at 2300 UTC 2



DOI: https://doi.org/10.30564/jgr.v4i3.3204

October 1993- 850hPa 355/8.24 m/s; 700 hPa 340/17.50 m/s; 320/24.71 m/s.

Upper winds at East Sale at 0500 UTC 3 October 1993- 600 m elevation 045/4.12 m/s; 900 m elevation 015/5.15 m/s; 1800 m elevation 290/11.33 m/s; 3600 m elevation 280/19.56 m/s; 4200 m elevation 275/22.6 m/s.

Upper winds at Wagga 0500 UTC 3 October 1993- 600mm elevation 340/17.50 m/s; 1200 m elevation 325/18.5 m/s; 3600 m elevation 330/23.68 m/s; 9900 m elevation 305/35.01 m/s.

Upper winds at Wagga at 1100 UTC 3 October 850 hPa 330/13.38 m/s;700 hPa 320/14.41 m/s; 500 hPa 300/17.50 m/s.

Upper winds at Wagga at 1700 UTC 3 October 1993- 1200 m elevation 005/12.36 m/s; 2100 m elevation 345/12.36 m/s; 3600 m elevation 325/14.41 m/s

### Melbourne widespread thunderstorm flash flood events 6-7 April 1977

Low developed VIC on Front Flash Flooding and Victorian Rainfall Records

Intense rainfall Laverton 7 Apr 1977 from 0515 UTC 7 April 1977 3:15 pm 137 mm in 3 hours; Wollert 7 Apr 1977 in 12 hours recorded 191 mm -Mt Ridley 7 Apr 1977 in 12h recorded 192 mm; Bentleigh East 7 Apr 1977 in 12 h recorded 203 mm.

24 h totals to 9 am 8 April 1977 CENTRAL – Laverton 188.0 mm, Epping 129.0 mm; Essendon 100.0 mm; Greenvale 118.6 mm; Glenroy 102.0 mm; Healesville 101.0 mm; Kinglake 136.8 mm; Kallista 109.2 mm; Hurstbridge 104.0 mm; Melbourne Ap 132.4 mm; Maroondah Weir 111.0 mm; Powelltown 129.8 mm Mickleham 190.0mm; Mt Dandenong 107.4 mm; Sherbrooke 111.8 mm; Warburton 111.0 mm; Whittlesea 114.8 mm; Woori Yallock 121.0 mm; Yan Yean 143.0 mm;

17 houses unroofed and trees brought down in Altona. 50 houses evacuated when Merri creek flooded.

Laverton upper winds 1700 UTC 6 April 1977 – 850 hPa 135/6.18 m/s; 700 hPa 020/10.30 m/s; 500 hPa 335/29.86 m/s.

Laverton upper winds 2300 UTC 6 April 1977 – 914 metres 135/18.02 m/s; 2133 metres 100/12.36 m/s; 3657 metres 095/7.2 m/s; 5486 metres 345/19.56 m/s.

Laverton upper winds 2300 UTC 7 April 1977 –850 hPa 190/18.53 m/s; 700 hPa 185/19.56 m/s; 500 hPa 175/25.74 m/s.

### December 2003 (Synoptic pattern in figure 12)

ARI 100 year flash flood event At Viewbank Automatic Weather Station (AWS) 27.0 mm was recorded in 14 min to 1439 UTC, 24.0 mm in 39 min to 1530 UTC and 76.2 mm was recorded between1425 UTC and 1530 UTC.

### Melbourne upper winds 1100 UTC 2 December 2003

925 hPa 010/7.21 m/s; 850 hPa 010/6.18 m/s 700 hPa 310/8.24 m/s 500 hPa 275/13.90 m/s.

### Melbourne upper winds 1700 UTC 2 December 2003

December 2016 (Synoptic pattern in Figure 13)

Special Climate Statement 59— The highest short-duration rainfalls during this storm were at Viewbank, in the north-eastern suburbs of Melbourne, where 40.2 millimetres fell in 15 minutes between 3.07 and 3.22 p.m. 29/12/2017.This is amongst the heaviest known rainfalls for such a duration in Victoria (Table 2) This rainfall rate surpassed the 1% annual exceedance probability rainfall (AEP)4 at all durations from 6 minutes to 6 hours, highlighting the very extreme nature of the rainfall

Melbourne equalled its highest dewpoint on record for any month, and December dewpoint records were set over many parts of Victoria, northern Tasmania, southern and western border areas of New South Wales, and the southern Northern Territory. In total, 21 long-term stations set December dewpoint records, with five of these setting records for any month. In Melbourne, the most immediately comparable events to the December 2016 event were those of January and February 2011. The December 2016 event had a slightly higher peak dewpoint (24.0 °C) than those recorded on 13 January 2011 (23.9 °C) or 4 February 2011 (23.2 °C)

Melbourne winds 2300 UTC 28 December 2016 925 hPa 340/15.4 m/s 850 hPa 310/12.3 m/s 700 hPa 300/13.90 m/s 500 hPa 300/14.93 m/s

### 4-5 February 2011(Synoptic pattern in Figure 14)

Around this time at 1100 UTC 4 February the routine radiosonde sounding at Melbourne showed a wind turning anticlockwise with height profile up to 700 hPa as follows: - 925 hPa 315/19.1 m/s; 850 hPa 310/16.0 m/s; 700 hPa 275/6.2 m/s. Further up to the northwest the heaviest rain at Mildura fell with 105.0 mm in 3 hours to 0700 UTC 4 February and the routine sounding at that station prior to this at 2300UTC 3 February showed the winds turning anti-cyclonically between 850 hPa 320/13.4 m/s and 500 hPa 300/10.3 m/s.

## 8. Mechanisms

The interaction of tropical air from the north and interacting with mid latitude weather systems approaching Victoria from the west is an important process in producing events with heavy rainfall over Victoria. In these systems wind structures can evolve which have flow patterns where the wind directions turn in an anticyclonic fashion from low up to mid-levels of the troposphere. Large scale ascent results from this wind structure aiding the development of rain and thunderstorms. This wind structure is particularly potent when there is cooler air aloft associated with it producing low static stability and extreme short-term rainfall can result. Low pressure systems along the east coast of Australia when they move closer to Victoria can produce the above wind structure over Eastern Victoria generating flood rains. This type of heavy rain system can also evolve from low pressure systems moving in from the west when there is tropical inflow of moist air on their eastern side.

## 9. Conclusions

Major flood and heavy rainfall events in Victoria which occurred since 1876 have been documented and these events were shown to have happened preferentially during positive phases of the Southern Oscillation (SOI). The synoptic weather patterns were analyzed and of the 319 events studied, 121 events were found to be East Coast Lows (ECLs) and 82 were other types of low-pressure systems. Tropical influences also played a large role with 105 events being associated with tropical air advection down to Victoria into weather systems. Examples were presented of all the major synoptic patterns identified. The 1976 Climate Shift and its influence on significant Victorian rainfall events were studied showing less periods of sustained monthly values of positive SOIs following the shift. It also showed increased occurrences of negative SOI events associated with the negative phases of the Indian Ocean Dipole following the shift. Despite this, one of the most active periods in Victoria's 144 years of heavy rainfall occurred after the Shift from 2007 to 2014 during a sustained period of positive SOIs so it remains to be seen if these extended positive phases continue in a similar fashion as occurred before the Climate Shift. It was shown how major Global Temperature rises were somehow related to this Climate Shift and needs to be understood more fully. A major period of Global warming occurred from 1915 to 1939 without obvious $CO_2$ emissions and positive SOI severe weather events dominated over this period even though Interdecadal Pacific Oscillation (IPO) data indicated a positive episode was operating and positive SOI events should have been far less prevalent. The cool season months of June and October were the months which had the largest event occurrences, June from ECLs and October with events affecting the Victorian Alps suggesting an influence from snow melts. Evidence was provided which showed the well documented reduction of cool season (April to October) heavy rainfall from around the time of the Climate Shift onwards. This seemed to be related to a lack of sustained sequences of monthly positive SOIs following the shift. Upper wind data available from some of the heaviest rainfall events showed the presence of anticyclonic turning of the winds between 850 hPa and 500 hPa levels which has been found to be linked with extreme rainfall around the globe.

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**REVIEW**

# State Restructuring and Urban Innovation Development in Post-reform China: Shanghai's Innovation Action in Review

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ARTICLE INFO

*Article history*
Received: 29 April 2021
Accepted: 04 June 2021
Published Online: 16 June 2021

*Keywords*:
State restructuring
Innovation activities
Urban development
Shanghai
China

ABSTRACT

Given the ample evidences from present studies on national-level innovation policies evolution and mechanisms, this paper contributes to a city-level understanding towards innovation-related state restructuring, the consequent innovation policy change and its relational performance with urban development in post-reform Shanghai, China from an input-output perspective. It unfolds that state restructuring relinquishing state power to the market has revived non-government innovation activities and a synchronous, though a bit backward, firms-oriented transition towards innovation development in Shanghai throughout 1990s has been observed. Though scholars are reluctant to label the party-state in post-reform China as a developmental state due to dysfunctionality of state intervention in corporate sectors, in the field of technological upgrading, such top-down, elite driven and state-sponsored mode giving priority to innovation competitiveness well captures the developmental state model at local level, thus exhibits elements of local developmental state. Impacts of this restructuring and policy change are substantial, which can be observed in the soaring increase of science and technology expenditures and patents applications in Shanghai. Additional analysis further unveils that in most circumstances, innovation growth kept paces with urban development, yet its synergy with economic development and permanent residents is more significant than with other aspects.

## 1. Introduction

State restructuring, referring to the decentralization of state power to the local and the market in post-reform China, profoundly remolds the geography of institutions and induces multi-scalar reorganization of state power at both the central and local level [1-3]. Interpreted in the work written by Brenner, state restructuring is inseparable from space of neoliberalism wherein the organization of state is not pre-given [4]. In other words, the state must cope with diverse array of mixed forces that technological progress is a significant one. Thus, it is not a surprise that the worldwide innovation fever resulting from state restructuring has witnessed an increasing state intervention

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DOI: https://doi.org/10.30564/jgr.v4i3.3173

at different geographical scales. While much literature on China's state restructuring has been preoccupied by its powerful effects on economic growth and urban transformation [5-8], less is noted on how this profound reform steers and reshapes innovation development, development that has increasingly become the key force for economic transition and upgrading. In few studies touched upon this topic, their primary focus is at the macroscopic national or regional level, interrogating how policies and spaces have evolved under the innovation related restructuring [1,9-11], whether innovation policies and its outputs in the cities synchronize those at the macro level and how they perform is less clear. We can simplify the urban-level innovation process as resulted from inno-state restructuring by which innovative activities are spatially evolved and resonant with local urban development. To enrich a city-level understanding towards innovation process against the backdrop of national state restructuring, this research interrogates how marketization of state power reshaped innovation landscapes and how related policy actions and urban development factors relate to urban innovation efficiency.

Shanghai has long been a progressive city as China's new, handy growth model [12] and illustrates central state's intentions for "molded, managed" capitalism with its emerging planned-market. Being a trading port since Qing Dynasty, Shanghai developed alongside the rise of modern China and has gradually evolved to a solid industrial base epitomizing China's modern industrialization, with intense intervention and power struggle from upper level governments. In most up-to-date orientation from the central state, Shanghai, alongside Beijing and Shenzhen, is shouldered to lead innovation development in the coming years, and serves an ideal case to illustrate urban innovation development and efficiency under the macro technological policy transition.

## 2. Innovation Policy and State Restructuring in Post-reform China

In China, science and technology (S&T) development has long been a commitment from the top design. Before the well-known market-oriented reform, public research organizations (PROs) stood by government and state-owned enterprises (SOEs) exempted from market competition were the principal executors for R&D [13]. A market-leaning innovative atmosphere arose in the 1978 National S&T Conference and was further ignited in 1985 that non-government R&D funding and technology activities appeared. In 1990s, the original PRO-centered innovation system had evolved firms-oriented, a shift fostering firms' innovation capabilities, commercializing technology, and enhancing efficiency of the innovation system [14,15]. Marketization pace has reached a peak during Zhu Rongji's premiership (1998-2003). Policy over S&T has been dissociated from heavy industry while natural and human scientific research was reiterated. Relaxation of state power to market has brought evidently less government intervention in high-tech sectors such as integrated circuit fabrication, nuclear power technology and civilian aircraft. But this doesn't mean that state support was no longer important. Instead, state has played a great role in launching and implementing key national innovation strategies. For instance, to implement the strategy of "revitalizing the Nation through Science and Education [*kejiao xingguo*]", the state raised budgetary allocation for the Chinese Academy of Science, increased grants approved by the National Natural Science Foundation of China, and invested large amount of funds to higher education institutions [9]. The state also insists on the open-door policy to allow foreign direct investment as a crucial channel for technology transfer and upgrading. To further integrate into the international market, the state paid more attention to intellectual property rights especially agreement on Trade-Related Aspects of Intellectual Property Rights [10].

Unleashing the power to facilitate innovation development in China has boomed the debates on whether post-socialist Chinese state can be characterized as developmental state (DS) as technological upgrading and innovative capabilities are key to the DS model [16-18]. Scholars working on DS point out that this model serves two main purposes: (1) to look beyond the American-Soviet comparison and (2) to connect interventionism with rapid economic growth happening anywhere in the world[19]. In general, theory of capitalist developmental state was earliest originated from explaining the East Asia industrialization (particularly Japan and the Four Dragons) under an ideal type of an interventionist state that was neither socialist nor free-market in nature [20]. In a capitalist developmental state, an "embedded autonomy" secures a social embeddedness to bureaucratic economic growth [21]. As Ronald Dore noted, the Japanese don't believe in the invisible hand, so that state-guidance and intervention are placed in the centerpieces of the DS model [22]. As a nationalist ideology prioritizing economic growth at the top of all the national affairs, the DS model also places the interests of the state over those of the individual, blurs the sphere between the public and private, pulses-on development as the most important legitimizing principle of the state, embraces plan rationality as opposed to market rationality, and selects autonomous technocratic, economic bureaucratic elites to serve the national interest [23].

Noteworthy, as proclaims by Johnson, this plan-rational growth model does not mean to exclude any private forces. Instead, they are allied with the state technocracies to serve the national goals, especially the development of competitive industrial sectors.

Indeed, scholars comparing China's growth pathway to that of the capitalist developmental states in the named East Asian countries are reluctant to label the Chinese post-socialist party-state as a developmental state, especially before 2000s [20]. In most cases, they tend to acknowledge that the operation of Chinese state, recognized by Castells as "state capitalism" or the "socialist market economy" [24], exhibits similar characteristics to that of DS (e.g. intentionally steer economy towards innovation) but is not identical to its archetype [25]. In innovation-related fields, China's main difference from the DS was found in the dysfunctionality, sometimes negative effects, of state intervention in the corporate sectors in the early days of reform [18,26]. In other words, the early destatization was not contributing much to China's entrepreneurship, it is the spontaneously developed town and village enterprises that went across the rivers by feeling the stones did [27,28]. This challenges the role and functions of the party-state in China's economic development. To many scholars, China's state restructuring characterized by dismantling of state power and fiscal decentralization had transformed local governments with strong developmental interest, formulating plans, attracting investment, and financing infrastructure to create economic miracles. Such developmental behaviors of local states were akin to those of its East Asian counterparts, and thus local developmental state (LDS). But as Zhu acknowledged, China's local state is a developmental state of its own kind [29], which is empowered by central government with economic autonomy and bear more liability for local prosperity but remains politically at the command of upper level government [28]. This can be verified in the strong control force of local government in the growth coalition formed by foreign, private and government sectors in urban redevelopment [30], as well as efficient execution of upper level command during the COVID-19 pandemic [31]. Yet, scholars also noticed that such developmental ideology did not always benefit the local. For instance, weak leverage of local government in guiding the market forces leads to the inferior and suboptimal built environment [29]. Policy coordination thus is necessary to better serve local sustainable development.

In view of the previous research findings, this paper assumes that in the field of innovation development, local governments in Chinese city reflect elements of the DS model, thus LDS in nature. And, through the perspective of policy evolution, this research further interrogates to what extent and in what aspect the LDS model capture the innovation evolution alongside the elapse of time, and how innovation outputs, under this evolution, relates to pros and cons of urban development in different time period. Shanghai pioneering in China's innovation strategy is selected as the case for a longitude study throughout 1985 to 2015 to generate insights for other cities. Diverse range of data such as patent records, archives, research such as published articles, statistical yearbooks, government working reports, local newspapers, and urban planning documents are broadly consulted.

## 3. Shanghai's Innovation in Action

### 3.1 Inputs from Local Government

*"Shanghai has been the center of a vortex of economic change spreading from the city to engulf the rest of China, and the pattern of its development during the past century has been modern China in microcosm"* [32]

Shanghai's policy and inputs on innovation development generally synchronize those at the macro level and represent another microcosm of innovative China. The local's innovative boom not only demonstrates a competent government action towards innovation but also reveals an efficient allocation of central state's vision for a powerful nation of science and technology.

#### 3.1.1 Policy Inputs on Innovation: Evolved Firm-centered, Open Sharing and State-market Hybrid

Since the first national S&T conference held in 1978, the role of Shanghai municipal government to foster innovation development has transited from a passive gatekeeper approving research projects and funding to an active planner making pro-innovation policies, organizing and coordinating macroscopic technological development. It showcases strong impetus to articulate the nation's marketization reform and visions for innovation and exhibits features of LDS in innovation policy making mainly in three aspects.

First, the government has made great efforts to steer non-state actors to be innovative and to release their innovation motives through policy initiatives and guidance for the national goals of innovative economy. In this regard, investment of science and technology is no longer purely government funded, but comes from diverse channels include NGOs, individuals and firms etc., in which firms evolved increasingly important in the local innovative boom. Specific measures include the effort to incent vitality of scientific and technical personnel, allows scientific



DOI: https://doi.org/10.30564/jgr.v4i3.3173

and technical staffs in the non-profit state supported R&D institutions to run their own companies for profit-making. Also, the main forces and preferential policies for technological progress have shifted from R&D institutions and universities to firms. By doing so, the government has opened up the enclosed innovation system and shaped it as market-oriented, firm-centered and political/industrial/academic/research-integrated. Second, the government has transited from providers of cheap labor and land absorbing foreign capital and technology, exemplified in the early established development zones (e.g. Minhang, Hongqiao, Caohejing), to pathfinders encouraging open sharing and nurturing local core- and high-tech firms, fundamentally practicing LDS that emphasizes indigenous impetus. At the national level, open door policy over S&T is amplified from usual communications, ordinary cooperation to joint development. Ideas of sharing are prioritized to chase the upper chain of R&D. In Shanghai, sharing part of the core technology should be a must when negotiating with foreign investors to settle. Also, in contrast to the traditional platform committed to serve narrow, specialized scientific research, technological service system has become more open sharing to foster high-technological clusters and new pillar industries, rather than merely focus on identifying technological potentials and transforming traditional industries. In such sense, Shanghai has been upgraded from a place transplanting advanced technologies from developed areas to an eco-system incubating up-to-date innovative ideas and nurturing new inventions. Third, innovation clusters are intentionally fostered and incorporated into urban spatial plans that are the regulatory product under a market economy. As the dragonhead in Yangtze River Delta, Shanghai got substantial policy supports from central government and formulated numerous planned for nurturing innovation activities. For instance, in the "22 opinions to promote Shanghai technology and innovation center", six innovation clusters including Zhangjiang, Zizhu, Yangpu, Caohejing, Jiading and Lingang are specially proposed. In the newly approved Shanghai master plan (2017-2035), a stratified innovation spatial system is planned. There are also knowledge-intensive universities and research institutes (e.g. Tongji knowledge economic industrial circle in Yangpu) contributing to the basic R&D and incorporated into these plans. All these initiatives represent a hybrid approach involving state-market interactions.

### 3.1.2 Investment Inputs on Innovation: Diverse Funds Dominated by Local Finance

Innovation inputs comprised of R&D investment, financial expenditure, infrastructural initiatives, and government service supports etc. are revealed in this section and related to broader institutional and policy changes. It is found that local finance dominates the innovation investment, with main sources come from firms since 2000. In the meanwhile, foreign investments are minimum and decreasing whereas funds from the governments are considerable and grow. Among the three types of innovation research, basic research receives the least funding support and the most money goes to experimental development. Firms still are the main executive departments and very few executions are from universities. In general, R&D investment and its ratio to GDP have increased yearly since mid-1980s, from 462 million RMB, 0.99% in 1985, 767.3 million RMB, 1.6% in 2000, to 104.9 billion RMB, 3.7% in 2016. S&T expenditure of local financial increases from 2.49 million RMB in 1985, 10.08 million RMB in 2000, to 341.71 million RMB in 2016, but its ratio to the total fluctuated in recent years, decreasing to a low ebb of 4.59% in 2008, arriving at a peak 7.2% in 2009 and declining thereafter.

Infrastructural initiatives to buttress innovative activities are primarily natural science-based, investment in social and humanity is nil in most years and has been very few until recently. The most dazzling infrastructural initiative is the large-scale scientific facility which contrib-

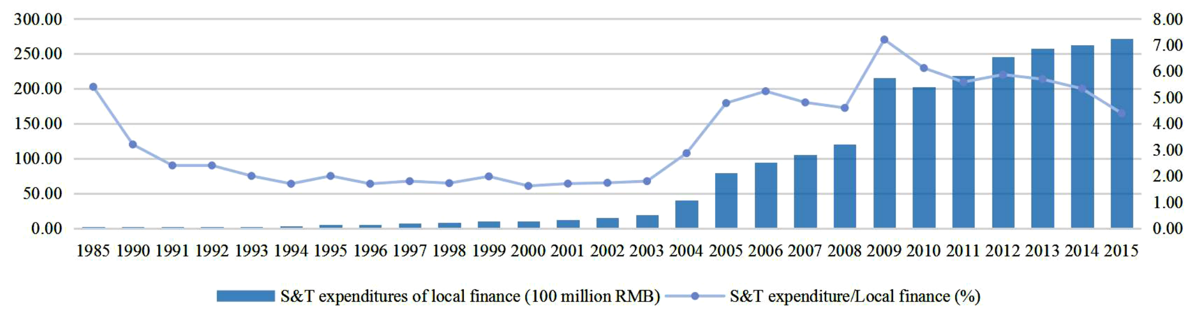


**Figure 1.** Financial expenditure on R&D and its ratio to local revenue

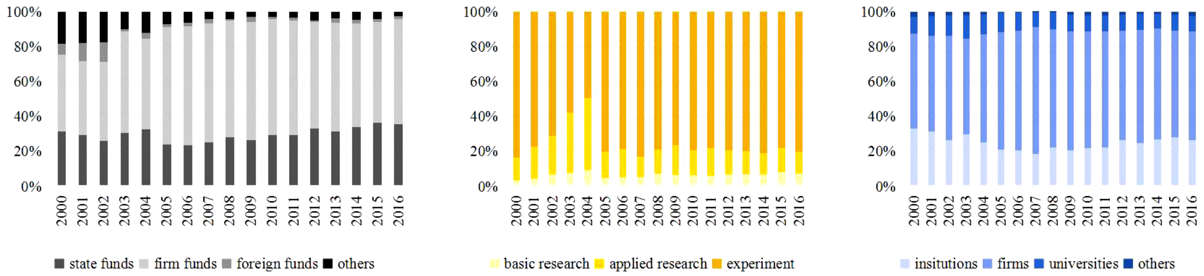


**Figure 2.** Sources of funds, types of innovation research and executive departments

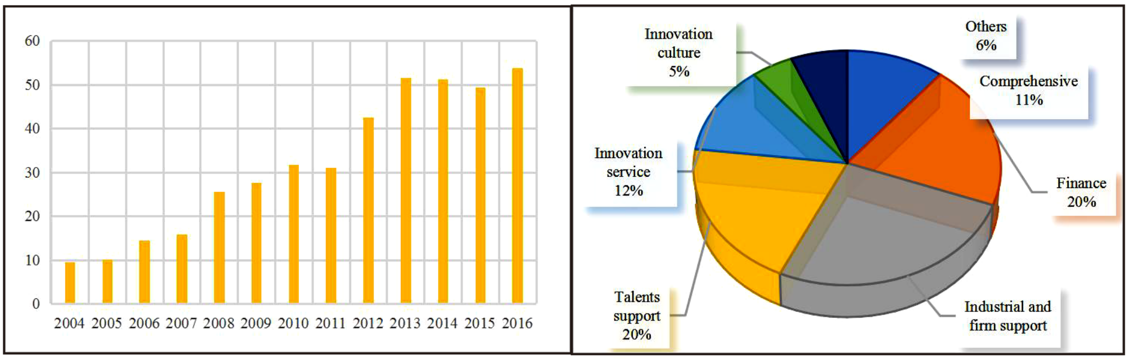


**Figure 3.** Natural science infrastructural investment and diverse government service supports

utes greatly to major innovations in Shanghai. Shanghai Synchrotron Radiation Facility (SSRF), National Center for Protein Science Shanghai and Submarine observation project are three topmost important large scale scientific facilities where most patents, scientific publications and new inventions come from. All these achievements are inseparable from government service support for innovation, which has undergone several stages for the past decades. From early to mid-2000s, advance intellectual property protection, commercialization of S&T, and financial investment rules on S&T enterprises were the main area of service support, protecting original innovation. Then, government had evolved to promote S&T finance and business service from mid to late 2000s, with the maturity of innovation policy system (marked by industrialization of high-tech) from late 2000s to mid-2010s, promoting commercial synergy with R&D. Since 2015 onwards, Shanghai's innovation has entered a new stage with many of the policy and institutional designs implemented to help a sustained, self-innovated development pathway. For instance, the "Opinion of Shanghai Municipal Party Committee and Shanghai Municipal People's Government on Accelerating the Construction of Globally Influential Science and Technology Center" and "Supporting Policies on Increasing Revenue Support to Accelerate the Construction of Globally Influential Science and Technology Center" were all promoted in 2015.

## 3.2 Outputs and Relational Aspects with Urban Development

### 3.2.1 Innovation Outputs: Evolved to Firm-dominated Pattern

Among the ways of measuring innovation outputs, this research deploys patent data which strongly correlated to R&D spending to showcase innovation intensity and knowledge production in Shanghai. Over 819,000 patent records applied from Shanghai since 1985 were identified from National Intellectual Property Administration. Each application records detailed information of patent type, application date, patent number, patent title, patent abstract, applicant, and applicant address with postcode. Though the initial 730 applications in 1985 were almost negligible, it signified a startup of Shanghai's innovation development. And, the increase of absolute number of patent applications has been up to 12 times in the past 17 years, surging from around 9,000 in 2000 to around 110,000 in 2016. Classifying patent records by the nature of the applicant (individual, firm, university and research institute, and authority), it is identified that individuals had been dominated the applications in early times, accounting 40%-50% before 1998 and reaching the peak of 52.1% in 1993. In all the 28,000 records between 1985 and 1999, 42% were from the individuals. Applications from universities were not negligible, with average 15% in 1980s and



DOI: https://doi.org/10.30564/jgr.v4i3.3173

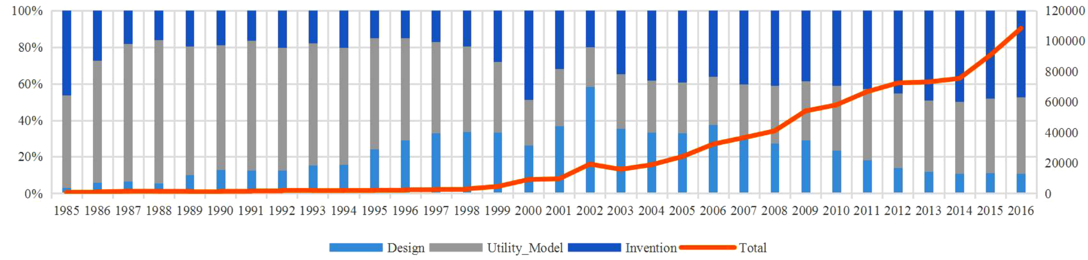


**Figure 4.** Three types of patents and growth trend by years (1985-2016)

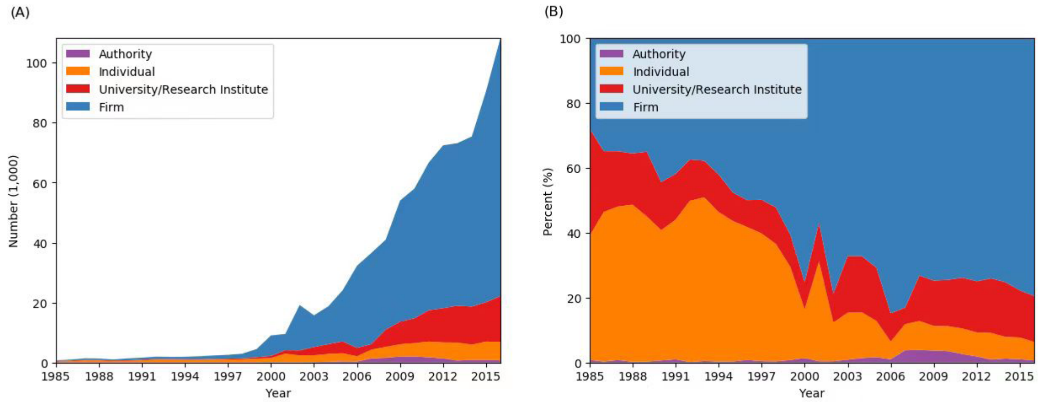


**Figure 5.** Patent applications by authorities, individuals, universities and research institutes, and firms (1985-2016)

1990s. Yet, ratio of records from both individuals and universities has diminished quickly though there has been an apparent upsurge of annual patent applications since 2000. The record shows that firms, contributing more than 60% of the total number, are the main sources of patent applications while university and research institutes contribute 10% to 20%. In contrast, individuals contribute much less and the share of it decreased from over 15% in 2000 to less than 5% in 2015. This has been in line with the policy supports to high-tech firms since 2000. Authorities refer to public entities that are not research oriented such as government sectors, primary and secondary schools, and armies. Their applications are minimal and kept dropping in recent years. Among the three types of patents, utility model led the growth before 2000 but invention has been increasing fast in recent years. Proportion of design reached the peak 58.4% in 2002 but has decreased rapidly since then.

Shanghai's booming innovation activities of firms accord against the general shift towards a firm-centered S&T model in China [33]. Before 2000, individuals, universities and research institutes were critical to China's innovation. Ratio of patent applications from firms were even lower than that from individuals during 1980s and 1990s [1]. Yet by late 1990s, innovation policies committed to developing high-tech industrial firms became prevalent, alongside a surge of new inventions from business [34]. Shanghai pioneered carrying out this policy transition and proposed policy packages to advance intellectual property protection, commercialization of S&T achievements, and financial investment on S&T enterprises①. The result is a gradual increased proportion of patent applications from firms after 2000. Sprawling of innovation activities also conformed with suburban development in Shanghai, in particular complied with its industrial suburbanization. Since 2000, Shanghai fostered a "1+3+9" spatial structure of industrial parks wherein "1" is Pudong New Area, "3" represents Caohejing Hi-Tech Industrial Park, Minhang Economic and Technology Development Zone, and Shanghai Chemical Industry Park, and "9" refer to Chongming, Jiading, Baoshan, Qingpu, Songjiang, Fengxian, Jinshan, Xinzhuang, and Kangqiao Industrial Development Zones. These industrial zones have nurtured a large number of firms investing and operating innovation production in outskirts. As part of the optimization strategy of Shanghai's metropolis structure, this industrial urbanization and its incubated innovation firms have reshaped the spatial layout of innovation-oriented capital accumulation [35].

① For instance, the "Notice of the Shanghai Municipality on Promoting the Transformation of New and High-tech Achievements" formulated in 2004, the "Shanghai Rising-Star Program" started in 2003, and the "Opinion of the Shanghai Municipality on Increasing Financial Service and Support for Technology-based SMEs" issued in 2009.

As patent applications before 2000 are negligible, this research has geocoded and mapped the patent records to reveal the spatial evolution of innovation activities after 2000 (Figure 6). Previous studies suggest that innovation activities tend to cluster spatially at the national or regional level [36-38]. Our analysis indicates that within the city, innovation activities are clustered in downtown and several major planned industrial base such as Zhangjiang, Zizu, and Caohejing. Innovation outputs along the expressway is eminent, from which we may assume that most of the innovation activities are related to manufacturing industries, which show high sensitivity of accessibility. Spatial growth of patent applications is a dual process: intensity of innovation activities kept concentrating in central city particularly in Puxi whereas innovation expansion towards suburb also persisted, moving towards south and north in the initial and diffusing across the metropolitan area after 2007. Innovation policy has profoundly influenced this process since 2000: improvement of innovative soft environment has further consolidated and optimized the innovation edge of central city as innovation infrastructure such as human resources, transportation, cultures and public services are enhanced. Alongside the "Opinion of Shanghai Municipal Party Committee and Shanghai Municipal People's Government on Accelerating the Construction of Globally Influential Science and Technology Center" and "Supporting Policies on Increasing Revenue Support to Accelerate the Construction of Globally Influential Science and Technology Center" promoted in 2015, Shanghai's innovation has entered a new stage with many of the policy and institutional designs implemented. Coping with the suburban policies, industrial parks as significant carriers for innovation activities thrived and facilitated expansion of innovation to outskirts where new industrial space takes shape and disperses.

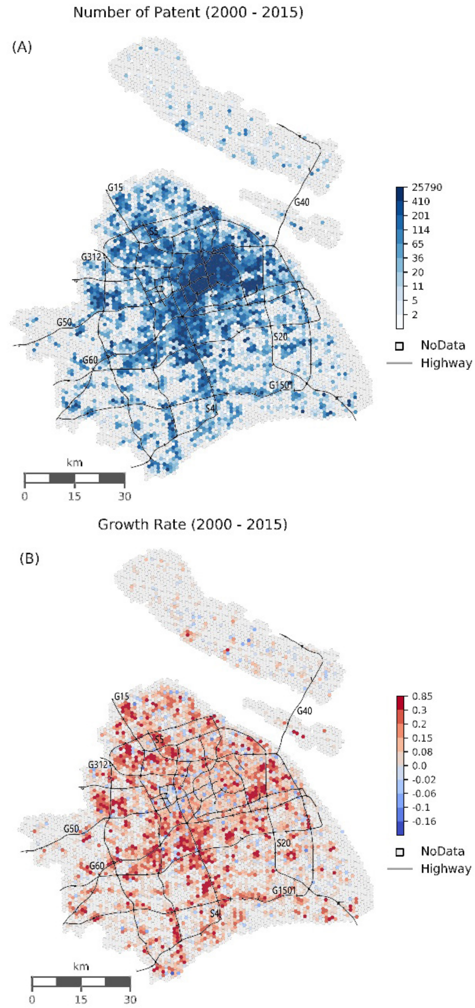


**Figure 6.** Cumulative spatial distribution of innovation activities in Shanghai (2000-2015)

### 3.2.2 Relational Aspects of Innovation Outputs with Urban Development

This research further inquiries into how innovation

**Table 1.** Compare indices of urban innovation and urban development

| Urban innovation index abbreviation | *Equation* | Positive/negative index |
|---|---|---|
| $IAGDP_s$ | $=\left((GDP_{t_2}-GDP_{t_1})/GDP_{t_1}\right)/\left((IA_{t_2}-IA_{t_1})/IA_{t_1}\right)$ | Positive |
| IAEngel | $=(Engel_{t_2}-Engel_{t_1})/(IA_{t_2}-IA_{t_1})$ | Negative |
| $IAPER_s$ | $=\left((PER_{t_2}-PER_{t_1})/PER_{t_1}\right)/\left((IA_{t_2}-IA_{t_1})/IA_{t_1}\right)$ | Positive |
| $IACC_s$ | $=\left((CC_{t_2}-CC_{t_1})/CC_{t_1}\right)/\left((IA_{t_2}-IA_{t_1})/IA_{t_1}\right)$ | Negative |
| $IAAQ_s$ | $=\left((AQ_{t_2}-AQ_{t_1})/AQ_{t_1}\right)/\left((IA_{t_2}-IA_{t_1})/IA_{t_1}\right)$ | Positive |

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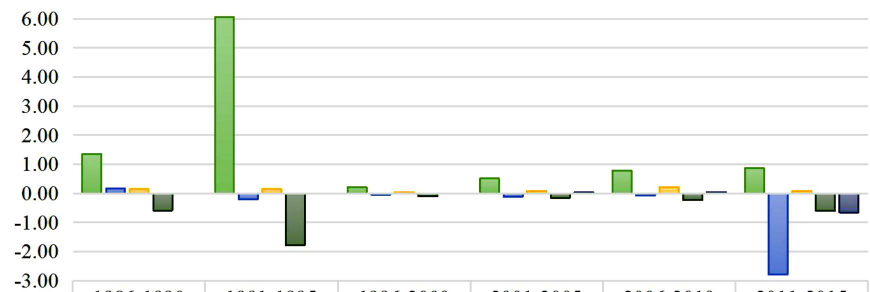


| | 1986-1990 | 1991-1995 | 1996-2000 | 2001-2005 | 2006-2010 | 2011-2015 |
|---|---|---|---|---|---|---|
| IAGDPs | 1.36 | 6.06 | 0.22 | 0.51 | 0.79 | 0.87 |
| IAEngel | 0.17 | -0.20 | -0.04 | -0.11 | -0.07 | -2.79 |
| IAPERs | 0.16 | 0.16 | 0.04 | 0.09 | 0.22 | 0.08 |
| IACCs | -0.59 | -1.78 | -0.10 | -0.15 | -0.22 | -0.60 |
| IAAQs | | | | 0.03 | 0.05 | -0.65 |

**Figure 7.** Comparison of innovation growth and the improvement of urban development level in Shanghai during six five-year plans (1986–2015)

relates to Shanghai's urban development of different dimensions by consulting the effects of innovation by years. A set of indices are developed to compare the growth rate of innovation and the level of urban development (Table 1). A five-dimensional indices representing urban development level are consulted. IAGDPs is the standard effect of urban innovation related to economic growth measured through growth rate of GDP divided by the growth rate of innovative activities. It is an economic index reflecting how innovation relates to economic performance and development level of the city. $IAPER_S$, $IACC_S$ and $IAAQ_S$ are standard effect of urban innovation related to permanent residents, Coal Consumption per GDP (kg/10,000 RMB) and air quality measured by a similar method. They reflect how innovation relates to the improvement of social development level, energy efficiency, and environment quality respectively. IAEngel is effect of urban innovation related to living standard improvement measured through growth rate of Engel coefficient divided by the growth rate of innovative activities. IAGDPs, IAPERs, and IAAQs are positive indices, meaning that the higher value the index is, the more innovation synchronizes with the particular dimension of urban development in this period. IAEngel and IACCs are negative indices manifesting the opposite meaning.

Most value fell between -1 and 1, implying that almost all the five dimensions of urban development level keep pace with the innovation development. Yet, differences remain visible. Almost in all the five-year intervals, growth of GDP and permanent residents positively related to innovation growth. However, only in the first two five-year periods, growth of GDP outpaced that of innovation. Since 1996, $IAGDP_s$ has been below 1, implying that the growth rate of GDP fell behind that of innovative activities, but this phenomenon has been mitigated with the increase of the value recently. Performance of living standard is unstable. Result of IAEngel was unsatisfactory at the initial, with coefficient increase alongside innovation increase. Situation gets better in early 1990s but worse again since 1996 as reduction rate of Engel coefficient became slower than increase rate of innovation growth. Yet a surprising trend emerges recently that IAEngel was lower than -2.5 from 2011 to 2015, meaning that improvement of living standard goes far beyond the innovation development. $IAPER_S$ value is positive but only has a small amount, meaning that permanent residents do not increase significantly when city has better performance in innovation. As long as Shanghai municipal government sticks to population control in the coming years, this trend may keep. From another perspective, this also means that innovation outputs per capita increase and that innovation density improves. Results of IACCs show a similar trend as IAGDPs. Decrease rate of coal consumption per GDP surpassed growth rate of innovation only in early 1990s, this trend has become much slower since mid-1990s but getting better recently (2011-2015). Air quality seems the most unsatisfactory dimension among all the five. Value of IAAQs decreases to minus 0.65, meaning that days with good air quality reduced and the reduction rate is non-negligible compared with the growth rate of innovation.

## 4. Conclusions

This research enriches the city-level understanding of state restructuring and the consequent urban innovation development, from an input-output perspective. Starting from a country-level review of state restructuring and the subsequent policy change of innovation, an increasingly active participation of non-state actors in innovation development with the elapse of time is identified. Though there have been divergent views towards whether the party-state in post-reform China can be label as a developmental state at the national level due to the initial dysfunctionality of state intervention in corporate sectors, findings of this research suggest that local government exhibits elements of LDS in innovation development, mainly from three aspects. First, the top-down, elite driven and state-sponsored growth mode giving priority to technological upgrading for innovation competitiveness in Shanghai case is considered the key to the developmental state model. Second, not only the state but also the non-state actors are motivated, collectively serving innovative economy to articulate the national goals. This is well illustrated in the synchronous, though a bit backward, policy transition towards firms-oriented innovation development in Shanghai throughout 1990s and the concomitant firm-dominated spatio-temporal patterns of innovation clusters development. Third, professional technocracies are widely involved to contribute their wisdom to this innovation boom, which is well exemplified in the policies, plans, regulations made to nurture innovation.

This research also draws some policy implications for innovation development in counterpart cities. First, stimulating market vitality can greatly improve innovative capability and outputs, which can be observed in the soaring increase of science and technology expenditures and patents applications in Shanghai since 2000s after the policy orientation evolved more marketized and firm-centered. In Shanghai, policy and spatial responses to state restructuring demonstrate an enhanced role of firms in innovation development. Under a pro-market ideology, policy support for firms overwhelms other type of innovation entities and firm innovation determines the spatial patterns and evolutionary trajectory of innovation in Shanghai. Second, the balance between innovation and urban development especially its potential negative effects on environment and social development shall be paid special attention to, as indicated in the fluctuated, unsatisfactory relational results of innovation and air quality as well as Engel coefficient. Third, a well infrastructural support especially rapid transportation system remains crucial for innovation development in cities like Shanghai where innovative activities concentrate alongside the expressway and show high sensitivity of accessibility. But policy makers should bear in mind that the chase to cutting-edge technology still has a long way to go as current innovation outputs, implied in the Shanghai case, remain at the stage of mass production technology upgrading with many invalid and revoked patents.

## Acknowledgments

This work was supported by The National Natural Science Foundation of China [No. 51808391].

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 DOI: https://doi.org/10.30564/jgr.v4i3.3173 

**Journal of Geographical Research**
https://ojs.bilpublishing.com/index.php/jgr

ARTICLE

# Land Recycling, Food Security and Technosols

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ARTICLE INFO

*Article history*
Received: 29 June 2021
Accepted: 29 July 2021
Published Online: 31 July 2021

*Keywords*:
Brownfields
Ecosystem services
Land take
Population growth
Sealed soils
Urban settlement

ABSTRACT

The world population will grow up to 9.8 billion by 2050. The intensification in urban growth will occur on all continents and in all sizes of cities, especially in developing countries, experiencing a greater rising in urban agglomerations of 300,000 to 500,000 people, those of 500,000 to 1 million and those of 1 to 5 million, by 2035. In this way, the demand of soil to host human activities (land take) will increase, mainly affecting soils with greater agricultural potential close to cities, at the same time as the need for food will increase. Land rehabilitation can contribute to human food security, to enhance ecosystem services and, if made by waste Technosols, those are viable as substrate for urban agroforestry systems. Although the references for brownfield reclamation for urban agriculture, adding constructed Technosols and de-sealed soils can recover its ecosystem functions even food supply services and would be the solution in urban areas.

## 1. Introduction

Trend of rising population and number of urban settlements around the world increases pressure on land take [1-3]. Consequently, it is a challenge for coming decades, related to fertile soil conservation, provision of ecosystem services and biodiversity [1,2]. Mainly due to loss of fertile agricultural soils, compromising their role as biomass producers.

In addition, land take implies in most cases soil sealing for the expansion or development of new urban settlements [2]. Therefore, the loss of soil functionality and its ability to provide ecosystem services is further aggravated. To counteract these shortcomings, the EU promotes land recycling prior to land taking. Since this practice is currently a minority in Europe [1] and many other parts in the world, we analyze whether sealed soils or brownfields can become functionally valid even as biomass producer (urban forestry areas).

In this sense, it is important to consider that soil, a finite resource, is one of the most important stores of carbon to combat global warming and at the same time [4,5], basic for human health.

Therefore, the purpose of this work is to know if loss of ecosystem services (including food provision) associated with land take on agricultural land due to urban expansion, can be counterbalanced with land rehabilitation as a solution that can be applied in many countries but

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  DOI: https://doi.org/10.30564/jgr.v4i3.3415

especially in developing countries and those with great percentage of soil sealed (i.e., in Europe). This rehabilitation can be of special interest in brownfields and by using made by wastes Technosols [5], and de-sealing soils.

## 2. Methodology

An analysis of literature related to consequences of population growth on arable land occupation, on ecosystem services provision and options to compensate this land take was done. This study is based on the need to determine if there is a qualitative relation between people, urban and soil sealing and try to improve the interest of administrations and research community about the problems associated to soil sealing and the solutions that can be applied.

For this purpose, internet search engines and scientific reference databases were used. The analysis was based on looking for the following key words (in the first step): population growth, agricultural land take, soil sealing, unsealing, de-sealed, de-sealing, brownfield, land recycling, brownfield, orchard, allotment garden, community garden, urban agriculture, Technosols, germination crops, food security. After that, a detailed study of the results was done, literature selected and complemented with the reports on Official Institutions websites mentioned in the reference section.

Population and settlement data were collected and processed by using dynamic tables and graphs in Excel (Office, ©Microsoft) and IBM® SPSS Statistics.

## 3. Urban Growth and Soil Sealing

The world's population in 2020 reached 7.7 billion people, and it is expected to continue increasing to 8.9 billion in 2035 and 9.8 billion in 2050 [6]. Considering the continents, it is expected an increase for all except Europe, which will experience a slight decline towards 2050 (Figure 1).

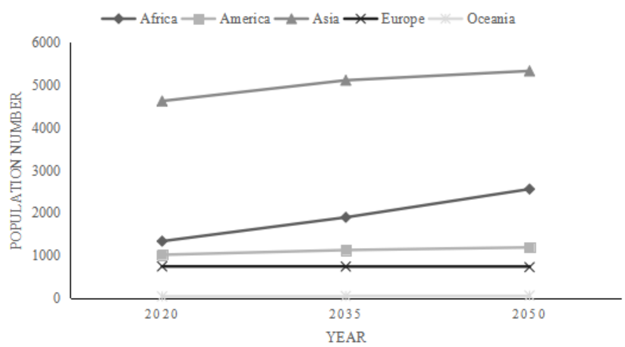


**Figure 1.** World population trends per continent expressed in millions of people (PRB, 2020).

Analyzing the settlement preferences of the world population in 2020, 56% choose urban environments for the development of their lives, which in quantitative terms is 4,353 million people. The urban population rate varies widely between continents and countries. Thus, in 2020, Asia is the continent with the largest urban population (2,359.26 million people), followed by America (815.2 million), Africa (575.34 million), Europe (560.25 million), and Oceania having the lowest number of urbanites (29.24 million people) [6]. The number of urban settlements also shows upward trends. In 2020 there are 1,934 registered cities around the world, and by 2035 it is estimated that they will increase to 2,363 [7], housing a population of 5,555 million people in 2035 (Figure 2) [8].

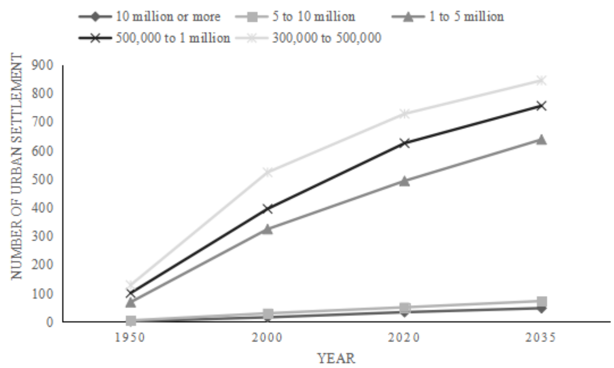


**Figure 2.** Number of world urban settlement trends (source: UN-HABITAT from UNDESA, 2020).

The intensification in urban agglomerations will occur on all continents and in all size of cities (Figure 3), although the increase in megacities (more than 10 million) is a phenomenon mainly associated with the Asian continent, which will increase from the current 21 megacities up to 32 megacities in 2035 [8].

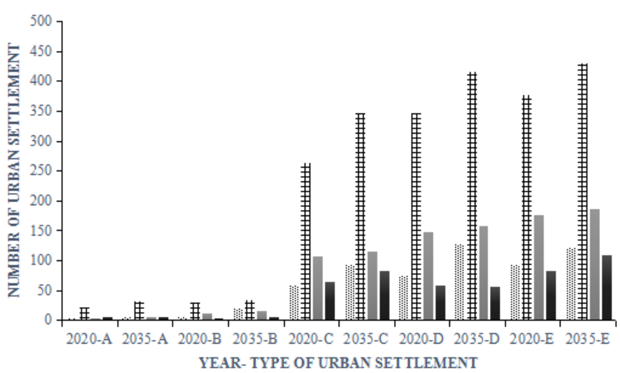


**Figure 3.** Continent type of urban settlement trends (2020-2035). In the figure, A: means urban settlement of 10 million people or more; B: 5 to 10 million; C: 1 to 5 million; D: 500,000 to 1 million and D: 300,000 to 500,000 urban people (source: UN-HABITAT from UNDESA, 2020).

Extending the study to the data given by international organisations [6-8], 141 countries have an urban population rate ≥ 50%, reaching 3,257.16 million of urbanites. This is notorious in countries like China, USA and Brazil.

The expansion of urban population leads to land take and land cover changes, as a support for the development of human activities (housing, industrial or infrastructure construction) [3]. In Europe, from 1990 to 2015, population growth by 2.4% triggered built-up areas by more than 30% [9]. Land taking in EU28, between 2012 and 2018, amounted to 539 $km^2$/year.

Land take, is a phenomenon that mainly takes place in peri-urban areas [2], areas that are associated with the highest quality soils for agricultural use [8,9] and the proximity food market. From 2000 to 2018 in EU28, more than 78% of occupied land affected agricultural areas, such as arable land and permanent crops (394.34 $km^2$/year), pastures and mosaic farmland (212.44 $km^2$/year) [12].

An immediate consequence of cropland decrease is the reduction in potential agricultural production capability to feed a growing population. In fact, Gardi et al. (2015) [3] estimated a loss of more than 6.2 tons of wheat (from 1990 to 2006) due to land take. This is a great concern in developing countries where it is more difficult to find accurate data of land take around the cities. In most of them, the immigration conditioned the increment of suburban areas with low health conditions and insufficient services and resources. This growth is directly associated to land take and soil sealing. Moreover, conditioned by an inexistent land planning and a disorderly occupation of the territory.

Moreover, as population and income levels increase, demand for food rise as well. Between 2000 and 2050, global demand for food crops projected to grow by 70-85% [13]. Meeting rising food needs in terms of both quantity and quality, puts additional pressure on productive capacity of arable fields that last, requires transform forest, semi-natural or natural areas into new agricultural fields, or implies relying on non-local food supply, which could compromise food security [11,14].

It is worth mentioning that loss of arable land is counterbalanced to some extent by increasing in agricultural productivity, but in the long term it will be necessary to use soils from forest or natural areas, which may not be so fertile and be far away [3], and by increasing intensive land management. This can lead to environmental damage [15], which carries an associated impact on a more global scale. Increasing food production through expansion of agriculture, only provides food supply services, but in return, has negative effects on other ecosystem services, such as water availability and quality, carbon sequestration, flood control, ecotourism potential and regulating services [13]. Owing to this, Hardaker et al. (2021) [16] studied the best practices options to enhance ecosystem services provision on arable lands.

In addition, detriment of present and future ecosystem services could be aggravated if soil is sealed. For instance, the percentage of total land take EU28, for green urban areas, between 2012 and 2018, is only 0.52%, the rest allocated to host activities with greater or lesser need to seal or remove the existing fertile soil [12].

Soil sealing defined as "the permanent covering of an area of land and its soil by impermeable artificial material (asphalt or concrete, for instance)". The average of soil sealed related to population growth, was estimated in 200 $m^2$ per citizen (by 2006) [11]. Added to consequences previously stated related to land take, soil sealing upsets environmental balance, because soil ecosystem is isolated from others. Impervious soil not only implies a reduction in capacity to provide ecosystem services, but also supposes provision of negative services (disservices) such as intensification of the urban heat island effect, increase risk of flooding, reduce filtering water that drains into aquifers and evapotranspiration, and adversely affect biodiversity and carbon cycle [3,10,16-19]. Consequently, Sobocká et al. (2021) [18] concludes that urban centers are the "most environmentally sensitive area" due to high rates of soil sealing (more than 80%) and urban heat island effects, and lack of green areas.

## 4. Soil De-sealing and Technosols

In 2020, 2.4% of soil is sealed and only 13% urban development on recycled urban land in Europe. Therefore, the European Union launched the mission "Caring for soil is caring for life", to ensure 75% of soils are healthy by 2030 for food, people, nature and climate [20], in the same line that many programs from FAO. Among the objectives set, is no net soil sealing and increase to 50% re-use of urban soil, aligned with no net land take by 2050. The net land take concept "combines land take with land return to non-artificial land categories (re-cultivation)", from urban area to semi-natural land [12]. Accordingly, European Commission proposes direct actions to avoid soil sealing, by reducing land take or by land recycling [15], because land taking mainly for sealing soils without restoring brownfield is unsustainable [10]. Land recycling means "redevelopment of previously developed land (brownfield) for economic purpose, ecological upgrading of land for the purpose of soft-use (green areas in the urban centers) and re-naturalisation of land (bringing it back to nature) by removing existing structures and/or de-sealing surfaces" [21].

Pytel et al. (2021) [22] proposed 8 possible transformation uses of brownfields, such as "cultural, didactic, natural, silvicultural, aquatic, economic, recreational and

  DOI: https://doi.org/10.30564/jgr.v4i3.3415

agricultural". In addition, we provide another option for brownfields reused, closely related to provision of ecosystem services, such as construction of wetlands or areas for water purification and run-off regulation [23]. All these new uses can be designed, to a greater or lesser extent, to host green urban areas with adequate ecosystem functionality, and a feasible option to avoid land occupation is to install on preserved constructions, green roofs and green walls. Land recycling for green spaces, can contribute to improve urban green infrastructure, and ecosystem services [10,11]. In fact, urban agriculture can develop on green roofs and walls [24], as well, on urban patches and plots of urban or suburban areas [25]. Nonetheless, in Europe brownfields restoration for green areas is a minority [10], which should be enhanced to compensate ecosystem services loss. Moreover, if reclaimed areas can be used for urban agriculture, it contributes to improvement of human health and food security [26,27].

Furthermore, Lal et al. (2021) [28] consider future land uses for sustainability of cities and megacities and for contributing to the fulfillment of Sustainable Development Goals (SDGs), are those related to urban garden, permaculture, vertical gardening and Technosols. Many cities use urban waste compost for urban agriculture [28], and consider viable incorporation of wastes as a substrate for plant species with agricultural utility [29,30].

Some constraints in the allocation of intended use are size of brownfields (areas between 1 and 20 hectares are suitable for green spaces) [22], soil state (contamination, fertility, among others) [23,31], and previous use mainly related to whether it has been sealed or not. Possibly this is due to the fact that brownfields of heavy industries show high rates of contaminated soils, so to avoid high costs of remediation, they are usually destined for secondary development [18]. Therefore, in the decision of the new use, economic criteria have priority over environmental or social ones [22,32]. Despite the fact that other interests prevail in the decision of the new use of brownfields, the relevance of the environmental benefits is unquestionable. Therefore, authors emphasize the importance of urban agriculture in carbon sequestration. Feliciano et al. (2018) [33], indicates that second largest absolute mean change in soil carbon sequestration reached from the implementation of a home garden on an underutilized land. Carbon sequestration related to agroforestry systems (soil and above ground), depends on "plant species, system characteristics, management factors, agro-ecological conditions and soil characteristics". Among the management factors highlighted by Feliciano et al. (2018) [33], is the use of residues from agroforestry systems [5]. In fact, Lal et al. (2021) [28] indicate that development of agroforestry systems or biochar addition are the only two methods to increase carbon sequestration capacity of soils in the long term.

In other matters, Pytel et al. (2021) [22] provide the most common form of land use in Poland is green spaces, mainly in previous landfills or mine dumps, where there is not an impervious layer. Followed by secondary use mainly associated with post-industrial brownfields. Accordingly, Klenosky et al. (2017) [34] indicate it is common to create green areas on brownfields from landfills. The area occupied by derelict and urban vacant land in Scotland in 2019 is 10,936 hectares, and only 20% of it considered uneconomic to develop or viewed as suitable to reclaim for a 'soft 'use [35]. Consequently, Pytel et al. (2021) [22] consider that new use of recycled land tends to coincide with the use immediately prior to the one that ended up in disuse, as its reconversion is cheaper and easier. Still, in Scotland in 2019, 405 hectares of 10,936 urban vacant hectares previously used for agricultural purposes, and only 13 hectares brought back into agriculture use [35]. For urban agriculture, in addition to soil contamination factor [26,27], soil fertility is limiting. The development project of a children's museum, for the improvement of nutritional habits and production of food in gardens, needed fertile soil and organic compost to replace poor topsoil [36].

Sobocká et al. (2021) [18] consider brownfields that have hosted highly polluting activities should not be reclaimed for residential development or housing the most sensitive population, nor for green parks, without proceeding to cover contaminated soil with a layer of topsoil (at least 50 cm). As indicate by Pecina et al. (2021) [31], for agricultural use it would also be advisable to be cautious [37]. As healthy soils generate healthy crops, which is crucial to human health and agricultural productivity [28]. Moreover, Deeb et al. (2020) [37] contemplate that constructed Technosols show great potential for brownfields restoration. De Sousa (2017) [32] indicates among remediation techniques for transformation of brownfields, the predominant is excavation, soil removal and backfill.

Therefore, at times, previous steep to green land recycling is de-sealing soil. Which implies, according to the European Commission, "Removing asphalt or concrete and replacing them with topsoil on subsoil" [15]. At this point, we wonder if it is necessary to use topsoil from elsewhere to restore de-sealed soils, if de-sealed soils can achieve ecosystem services levels prior to sealing, and if so, if de-sealed soils can become biomass producers. Sealed soils experience an alteration of their properties, worse soil structure and organic matter, and moderate to high amount of trace elements, leading to a drastic reduction in microbial community, among others aftermaths [17,18]. In cases where it is completely necessary to add topsoil on de-sealed soils, an option to consider may be incorporation of Technosols made by wastes, to enhance ecosystem services [38]. It could be a new line of research, as authors have not found references in this context. Authors consider sealed soil is not a reversible process [39]. Maybe this needs more discussion, depending on removing impervious layer or not. In fact, Tobias et al. (2018) [10] consider all de-sealed brownfields have potential for providing ecosystem services if soil is restored. Recent references conclude de-sealed soils can restore their quality and fertility, by themselves, without adding topsoil [40]. De-sealed soils can even improve functional and biological levels, with shrub planting and irrigation.

As indicated by the aforementioned references, de-sealed soils can recover their ecosystem functions. However, would it also include the provision of food? Authors aim to discern if it is a feasible option to balance the loss of fertile soil for agricultural use, with de-sealed urban soil. The conclusions of Tobias et al. (2018) [10], establish sealed soils with agricultural potential can reclaimed for food production, although at times the degree of soil compaction may be limiting. In addition, it would be convenient to know if de-sealed soils may need additional treatments and on what timescale, to become suitable for agricultural re-use. This paper [41], addressed this question, concluding de-sealed soils, without any additional treatment, only allowing colonization of spontaneous vegetation, improve their physical and chemical fertility. Even more, this can increase microbial biomass and biochemical activity, exceeding the values of agricultural soils.

Research is needed in this sense, because there were scarce references related to brownfield reclamation (sealed or not) for urban agriculture and using made by waste Technosols for improving soil properties and functions. Technosols and the use of wastes can be a solution, mostly of them that can be considered as bioresources coming for many activities (i.e., food waste) [42].

## 5. Conclusions

In 2020, the countries with more than half of their population in urban environments cover most of the habitable terrestrial territory. The expected increase in population will be associated with a rise in the number and size of cities worldwide (in Europe, the cities that will increase the most will be those with 500,000 to 1 million and those with 300,000 to 500,000 inhabitants), as well, with land take mainly affecting fertile soils. Consequently, it will be a challenge for food supply, food security and to provide ecosystem services.

Furthermore, most of the soil affected by land take is sealed, which implies provision of ecosystem disservices. To counteract it, the European Union, in addition to limiting land take, is promoting land recycling. Land recycling for green areas can enhance ecosystem services, an adding Technosols made by wastes, increase sustainability of cities and megacities, improve agricultural productivity and human health. Consequently, brownfield regeneration may go beyond constructing of new facilities that have an aesthetic, productive or recreational use, with the implementation of green areas.

At the same time, it would be advisable to avoid using natural soil to fill, bioremediate, or improve soil properties for urban agriculture, since the incorporation of Technosols as a substrate for crops, support of green areas and forest urban areas is a viable option. Besides, using de-sealed soils after rehabilitation for agricultural production seems to be a real possibility.

More information on land rehabilitation, Technosols and de-sealed soils for urban arable land uses would help us to establish a greater degree of accuracy on this matter. So, new research and data supporting urban soil rehabilitation should be a target for local, regional and national administrations in order to improve our health and urban environments.

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  DOI: https://doi.org/10.30564/jgr.v4i3.3415

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# Spatial Heterogeneity Association of HIV Incidence with Socio-economic Factors in Zimbabwe

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ARTICLE INFO

*Article history*
Received: 15 July 2021
Accepted: 30 July 2021
Published Online: 31 July 2021

*Keywords*:
HIV and AIDS
Spatial modelling
Geographical weighted Poisson regression model
Socio-economic factors
Zimbabwe

ABSTRACT

This study examined the spatial heterogeneity association of HIV incidence and socio-economic factors including poverty severity index, permanently employed females and males, unemployed females, percentage of poor households i.e., poverty prevalence, night lights index, literacy rate, household food security, and Gini index at district level in Zimbabwe. A mix of spatial analysis methods including Poisson model based on original log likelihood ratios (LLR), global Moran's *I*, local indicator of spatial association - LISA were employed to determine the HIV hotspots. Geographically Weighted Poisson Regression (GWPR) and semi-parametric GWPR (s-GWPR) were used to determine the spatial association between HIV incidence and socio-economic factors. HIV incidence (number of cases per 1000) ranged from 0.6 (Buhera district) to 13.30 (Mangwe district). Spatial clustering of HIV incidence was observed (Global Moran's *I* = - 0.150; Z score 3.038; *p*-value 0.002). Significant clusters of HIV were observed at district level. HIV incidence and its association with socio-economic factors varied across the districts except percentage of females unemployed. Intervention programmes to reduce HIV incidence should address the identified socio-economic factors at district level.

## 1. Introduction

Approximately 36.7 million people are living with HIV and AIDS worldwide, with 1.8 million new infections and one million AIDS related deaths yearly [1]. Globally, the highest burden of the HIV & AIDS pandemic is in East and Southern Africa where 800 000 new infections are recorded yearly, leading to 20.6 million people living with the disease, and 310 000 related deaths [2]. This calls for renewed obligation and improved tools and methods to reduce HIV infections especially in developing countries including sub-Saharan Africa [3].

The relationship between HIV infections and socio-economic factors including poverty, education, food insecurity and employment is complex [4]. There is a consensus among scholars that HIV can lead to deteriorated socio-economic conditions (poverty in particular) at individual and household level [5]. In fact, poverty impedes

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 DOI: https://doi.org/10.30564/jgr.v4i3.3466

access to preventive actions, healthcare and information thereby increasing the susceptibility of people to HIV infection [6]. Contrary to this, poverty is considered to be one of the major drivers of HIV epidemics [7]. Although HIV is not always concentrated among the poorest populations it is believed that socio-economic factors may act as a distal determinant of infection [4]. Poverty may lead to adoption of high-risk sexual behaviour or practices including earlier sexual debut, earlier marriages, and transactional sex for income generation [7]. Such practices increase the risk of acquiring HIV, especially among the young and poor women who mostly depend on men to earn a living [4].

However, Gillespie et al. [8] noted that the perception that poverty is the major contributing factor of HIV transmission is too simplistic because relative wealth has diverse effects on HIV risk. This view is supported by studies that showed that HIV infections can also be higher among wealthier people [9-11] who indulge in risky sexual practices involving multiple partners. Gender is also an important driver for HIV transmission particularly in the case of poverty/wealth relationships [7,8]. Poorer and less-educated women may be less knowledgeable about HIV risks and therefore less able to adopt the needed risk-reducing behaviour [4]. Some studies have suggested that relative wealth initially can increase HIV risk, but may become a protective factor as epidemics mature [12,8]. However, it is unclear whether this trend can occur in circumstances of rapid macro-economic changes [7].

Since year 2000, Zimbabwe has been experiencing serious economic challenges that have disproportionally affected the socio-economic conditions of people across various districts [13]. Despite recording remarkable progress in reducing HIV prevalence and incidence, wide variations still remain across districts of Zimbabwe and the HIV burden is still high among adolescent girls and young women than in men (15.3 percent vs. 10.2 percent) [14]. This disparity in socio-economic challenges experienced across districts indicates the need to determine the spatial variation of HIV incidence and its association with socio-economic factors at district level thus warranting further research to understand the contributing socio-economic factors to these variations at district level.

Most of the recent studies in Africa, Zimbabwe included, have considered the modelling of spatial variation of HIV prevalence at fine resolution such as 5km X 5km pixel. The training data for these models is mostly derived from health facilities and testing centers which are then extrapolated to pixel level based on interpolation methods including kriging and co-kriging [15-17]. Such studies would complement Pascoe et al. [4] and Schur et al. [7] who considered non spatial dimensions of this relationship in Zimbabwe. Our study was therefore intended to address the gaps by examining the spatial heterogeneity association of HIV incidence and socio-economic factors in Zimbabwe. We complemented established models through an analysis of spatial variation of HIV incidence in relation to socio-economic factors at district level focusing on the spatial heterogeneity association of HIV incidence and socio-economic factors.

## 2. Materials and Methods

### 2.1 Study Area

This study was conducted in Zimbabwe, which is located in Southern Africa (Figure 1). Zimbabwe has an approximate population of 14 million with 60% of people living in rural areas [18]. It has 10 provinces and 62 rural districts. Zimbabwe has a predominantly young population with about 61% of the population below the age of 24. Females constitute 52% of the total population [19]. The economy of Zimbabwe is based on agriculture, which contributes approximately 13% of its gross domestic product (GDP) [20]. Zimbabwe is in the low human development class ranking 156 out of 189 countries based on Human Development Index (HDI) [21]. The country experienced a decline in the incidence rate from 0.74 in 2014 to 0.49 in 2017 and 0.38 in 2020 [22,23]. The HIV prevalence varies across the districts. For example, in 2017 Bulilima district had the highest adult prevalence (23%) while Gokwe North had the lowest (9%) [22]. In 2015 the incidence of poverty was lower in urban compared to rural areas indicating that inequality levels varied between rural and urban settings in Zimbabwe [18]. Income inequality estimated using the Gini coefficient also varies across districts as determined by the respective economic activities. These disparities, among others, may contribute to the spatial distribution or variation of HIV and AIDS incidence in Zimbabwe.

### 2.2 Datasets

Data used in this study include (i) estimated cases of HIV for 2017 obtained from the Ministry of Health and Child Care [22]; and (ii) district socio-economic factors from the 2017 Poverty, Income, Consumption and Expenditure Survey (PICES) and Poverty reports, and Zimbabwe 2012 census data (http://www.nada.zimstat.co.zw/). These were the current and complete datasets available at the time of study. The socio-economic variables we used were poverty severity index, percentage of females employed permanently, percentage of females unemployed, percentage of male population employed permanently, night-lights index, and percentages of male and female lit-

  DOI: https://doi.org/10.30564/jgr.v4i3.3466

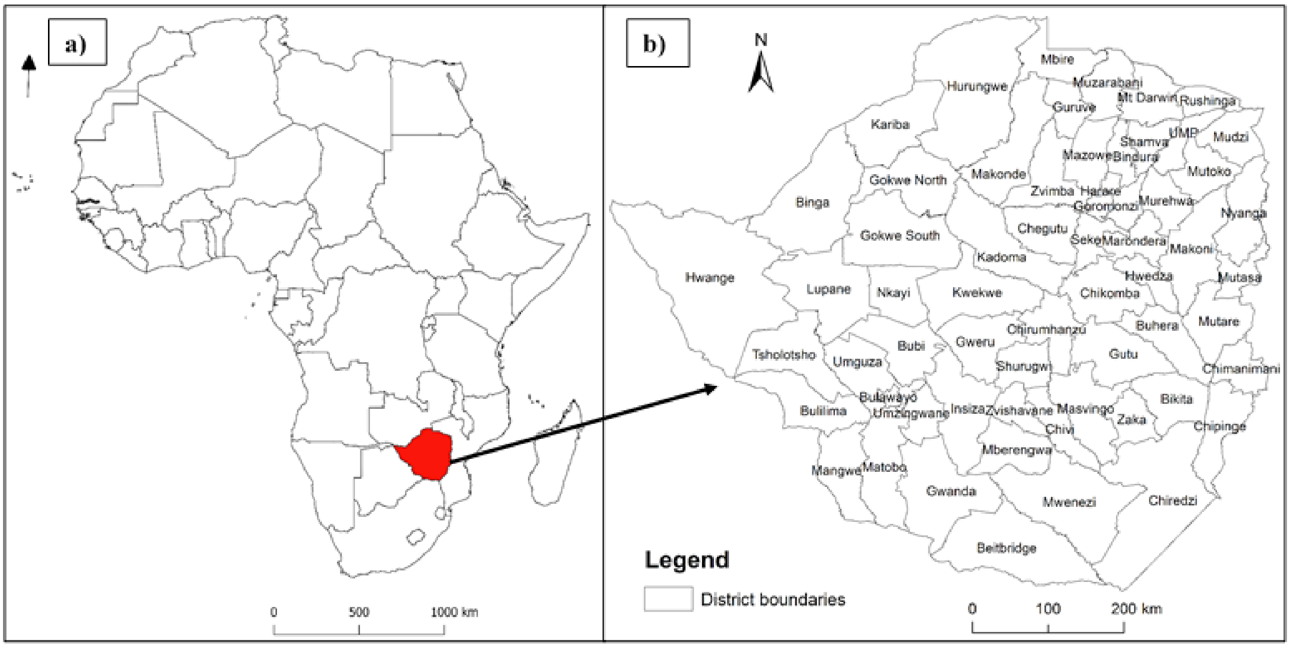


**Figure 1.** Study Area, a) location of Zimbabwe in Africa and, b) Zimbabwe district boundaries.

eracy, percentage of poor households in each district, the Gini index and the household food insecurity.

The selection of socio-economic factors was based on previous studies which proved their effects on the variation of HIV and AIDS [8,6]. For example, high poverty severity correlates very well with high incidences of HIV [5]. In a similar way, high percentages of male and female participation in the labour force reflect increases in economic productivity that enhance preventive actions, access to healthcare and information that reduce HIV infection [6]. Likewise, a higher literacy rate among the gender groups enhances the capability of the population groups to prevent the spread of HIV [4]. We also included the Night Lights Data (NLD), a satellite dataset (from NOAA National Centers for Environmental Information, https://ngdc.noaa.gov/eog/d msp/downloadV4co mposites.html) which has been widely used as a proxy for local GDP and for measuring poverty. Light is essential for the consumption of any good or service at night hence the increase in light intensity may imply increases in economic activity or welfare [24]. Most of the economic activities in developing countries including Zimbabwe are informal and that makes data collection difficult resulting in poor quality of the data [24], thus NLD give the unbiased measure of spatial economic activity in Zimbabwe. Table 1 summarises the socio-economic factors used in this study.

**Table 1.** Summary of socio-economic variables used at district level in Zimbabwe

| Variable | Minimum | Mean | Maximum |
|---|---|---|---|
| Poverty Severity Index | 1.8 | 16.710 | 36.60 |
| Females employed Permanently (%) | 1.1 | 8.077 | 30.10 |
| Females unemployed (%) | 0 | 4.460 | 41.08 |
| Male employed permanently (%) | 2.3 | 13.7 | 29.30 |
| Poor Households (%) | 4.9 | 16.934 | 100.00 |
| Night Lights index (Max value) | 0 | 19.049 | 63.00 |
| Male literacy rate (%) | 93 | 96.537 | 99.00 |
| Female literacy rate (%) | 86 | 94.183 | 98.17 |
| Household food insecurity (%) | 33.2 | 55.48 | 85.1 |
| Gini index | 31.5 | 46.0 | 36.79 |

## 2.3 Data Analysis

To understand the spatial distribution of HIV incidence, independent of the exploratory variables and in association with the socio-economic factors, we applied the Poisson model because data on HIV and AIDS cases is known to follow independent Poisson distributions [6]. The subsequent sections explain the three analyses we performed in this study.

### 2.3.1 Spatial Distribution/Clusters of HIV

Since HIV prevalence varies in space, flex scan statistic, Global Moran's I and LISA were employed to as-certain geographical clusters of elevated HIV infections. Using ArcGIS10.4, four types of clusters are observed through LISA: (1) high-high, which means that high values are bordered by high values; (2) low-high, a low value was surrounded by high values; (3) high-low, a high value is bordered by low values; and (4) low-low, a low value was surrounded by low values. High-high and low-low denotes positive spatial autocorrelation and areas of contradictory values i.e., low-high and high-low indicates negative spatial autocorrelation [25].

We used the Poisson model based on original log likelihood ratios (LLR) with flexible scanning method and the maximum cluster size of 15 (default) and Monte Carlo replications to determine the spatial clusters of HIV incidence at district level in Tango's flexibly shaped spatial scan statistic (FlexScan), FleXScan v3.1.2 [26]. Higher risk rates were related with higher LLRs. The methods for calculating the likelihood ratio (LR) and LLR are given in detail by Tango and Takahashi [27] and Takahashi and Shimadzu [28].

### 2.3.2 Spatial Regression Analysis

Geographically Weighted Poisson Regression (GWPR) analysis was performed in GWR4.09 to determine the spatial variation of the association between 2017 new cases of HIV and the related socio-economic factors at district level. Three forms of GWPR were considered in this study and their performance was compared based on Akaike information criterion that has a correction for small sample sizes (AICc) [29]. The first one is the global Poisson model, which assumes no spatial variation of the coefficients for the exploratory variables of the disease. The second one is GWPR, which assumes that all the exploratory variables in this case the socio-economic variable vary locally (Equation 1). The third one is semi-parametric GWPR, which assumes that some variables vary locally. Hence, they are termed local while those that do not vary are known as global variables (Equation 2).

$$y_i \sim \text{Poisson}\left[N_i \exp\left(\sum_k \beta_k(u_i, v_i) x_{k,i}\right)\right] \quad \text{(Equation 1)}$$

$$y_i \sim \text{Poisson}\left[N_i \exp\left(\sum_k \beta_k(u_i, v_i) x_{k,i} + \sum_l \gamma_l z_{l,j}\right)\right] \quad \text{(Equation 2)}$$

Where  is the dependent variable, which has to be an integer greater than or equal to 0.  is offset variable (population at risk) at the *i*th location and in this case total population per district; is the *k*th independent variable  is the x-y coordinate of the *i*th location; and coefficients  are varying conditionals on the location. is the *l*th independent variable with a fixed coefficient

The fixed bi-square (Equation 3) was the geographical kernel with the best performance based on AICc.

$$w_{ij} = \begin{cases} \left(1 - d_{ij}^2/\theta^2\right)^2 & d_{ij} < \theta \\ 0 & d_{ij} > \theta \end{cases} \quad \text{(Equation 3)}$$

Where *wij* is the weight value of observation at location *j* for estimating the coefficient at location *i*; *i* is the regression point index; *j* is the locational index; *dij* is the Euclidean distance between *i* and *j*;  is a fixed bandwidth size defined by a distance metric measure. The Golden search method was used for optimal bandwidth search. This automatically selected the optimum bandwidth size as defined by the performance assessment criteria and in this case the AICc.

Both GWPR and s-GWPR provided locally varying parameter estimates, for local variables and their *pseudo* t values [30]. *Pseudo* t values less than − 1.96 or greater than + 1.96 designates p-values < 0.05 indicating the significance of the locally varying parameters [30,31]. Comparison of the small sample size bias corrected AICc and the percent deviance explained were used to determine the model with the best performance [29,4]. Small values of the model signify a better performing model. If the difference between AICc is greater than 2, the model with lower AICc is chosen [32]. The model with the highest percent deviance explained is better performing. The local coefficients maps showed districts with significant estimates.

### 2.3.3 Multicollinearity

Multicollinearity was determined based on the variance inflation factor (VIF). The variables which had VIF greater than 5 [33] suggest severe multicollinearity. Hence female literacy rate was not considered in the analysis consistent with other similar studies [4,34,31].

## 3. Results

### 3.1 Spatial Variation of HIV in Zimbabwe

HIV incidence (number of cases per 1000) ranged from 0.6 (Buhera district) to 13.30 (Mangwe district). Spatial clustering of HIV incidence was observed (Global Moran's $I$ = - 0.150; Z score 3.038; $p$-value 0.002). Significant clusters of HIV were observed at district level. Figure 2(a) shows the spatial variation of HIV incidence based on standard deviation and the location of clusters from Tango's FlexScan while 2(b) shows HIV incidence hotspots or clusters based on LISA. As shown in Figure 2(a), HIV incidences are mostly concentrated in Bulilima, Mangwe, Umguza, Umzingwane, Bubi, Insiza, Zvishavane and Shurugwi district. Table 2 gives the details of the clusters from FlexScan. HIV is mostly clustered in Bubi, Bulilima, Insiza, Mangwe, Shurugwi, Umguza, Umzingwane and Zvishavane (Table 2). Other high-rank-

  DOI: https://doi.org/10.30564/jgr.v4i3.3466

ing secondary clusters are found in Hurungwe, Buhera, Chikomba, Chirumhanzu, Hwedza and Seke. Districts from the western through to the central and northern part of the country had high level of deviation from the mean HIV incidence (Figure 2a). Two types of clusters were observed through LISA: (1) high-high, which means that a district with high value of HIV incidence was surrounded by district with high values; (2) low-high, a district with low value of HIV incidence was surrounded by districts with high values. The high-high cluster includes Bililima, Mangwe, Umguza, Bubi Umzingwane, Zvishavane and Shurugwi district. All the high-high clusters fall within the most likely cluster identified through Poisson based original LLR with flexible scanning method in FleXScan. The low-high cluster is made up of Matobo district.

### 3.2 Regression Model Selection

Fixed bi-square was used as a geographical kernel and the best bandwidth size for all the models was 323.824 km based on golden search for optimum bandwidth. This means that HIV incidence or new cases in the district within 323.824 km were used in estimating the coeffi-

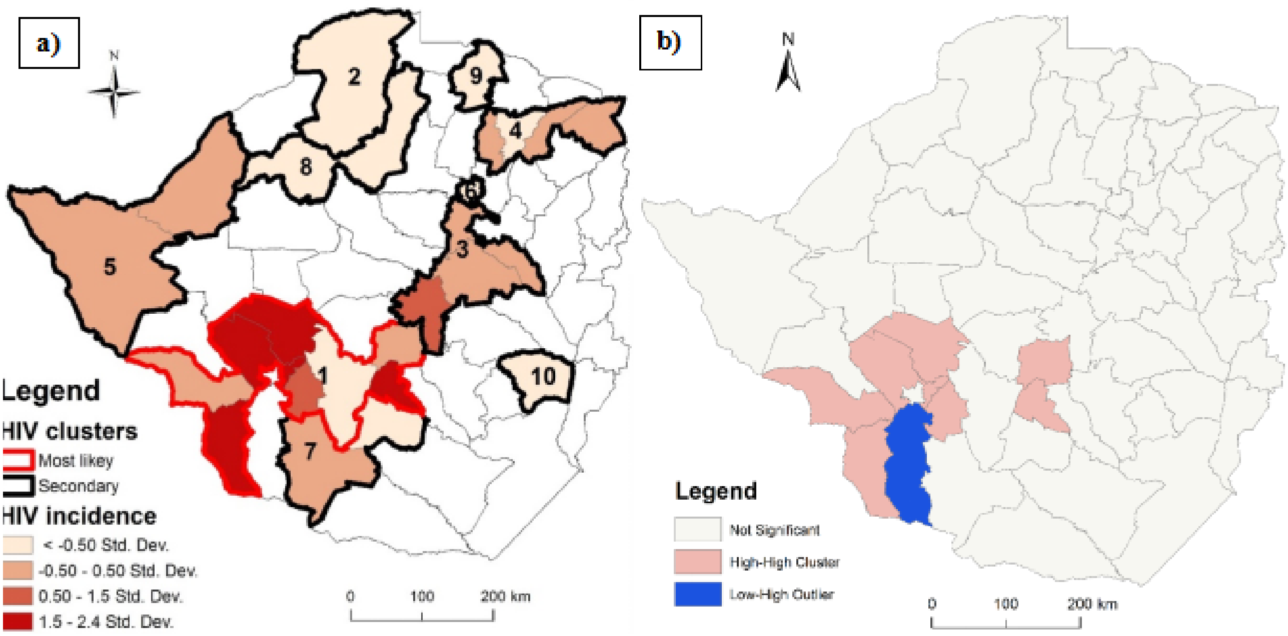


**Figure 2.** (a) Spatial variation of HIV incidence based on standard deviation and the location of clusters from Tango's FlexScan (b) HIV incidence hotspots or clusters based on LISA

**Table 2.** Characteristics of the clusters identified through flex scan as shown in Figure 2a

| Cluster ID | Characteristics | | | |
|---|---|---|---|---|
| | Districts included | Number of cases | Expected number of cases | Overall relative risk |
| Most likely | | | | |
| 1 | Bubi, Bulilima, Insiza, Mangwe, Shurugwi, Umguza, Umzingwane, Zvishavane | 6650 | 3020.49 | 2.202 |
| Secondary | | | | |
| 2 | Hurungwe | 1300 | 166.156 | 7.824 |
| 3 | Buhera, Chikomba, Chirumhanzu, Hwedza, Seke | 2950 | 1726.84 | 1.708 |
| 4 | Bindura, Mudzi, Shamva, UMP | 3460 | 2219.38 | 1.559 |
| 5 | Binga, Hwange | 1700 | 1032.54 | 1.646 |
| 6 | Harare | 10000 | 8901.24 | 1.123 |
| 7 | Gwanda, Mberengwa | 1620 | 1329.25 | 1.219 |
| 8 | Gokwe North, Makonde | 2110 | 1780.25 | 1.185 |
| 9 | Muzarabani | 650 | 492.535 | 1.320 |
| 10 | Bikita | 750 | 593.416 | 1.264 |

cients at district of interest i.e., the regression point index. This bandwidth size had the lowest AICc (6163.638). The s-GWPR with percentage of females unemployed as a fixed or global variable and other variables as local (i.e., intercept, poverty severity index, females employed permanent, females unemployed, males employed permanent, poor households) outperformed other models considered in this study based on AICc. There were large differences between its AICc and Poisson global and GWPR i.e., 6402.392 and 27.335 respectively. It had the highest percent deviance explained of 0.602. These results show that most of the variables that explain the spatial variation of HIV incidence or new cases vary across the districts except a few such as females unemployed which do not vary by district. This indicates that models which incorporate local and global variables help to explain the variation of HIV incidence across the districts. More details on the variation of the contribution of these factors from the best model (i.e s-GWPR) are given in the next section.

### 3.3 Local Variation of Exploratory Variables in Determining the Heterogeneity of HIV Incidence

The s-GWPR model had one variable - Females unemployed (percentage) as global variable with a coefficient value of 0.165, standard error (0.014) and z-value of 11.803. The maps in Figure 3 and Table 3 show the spatial variability of the exploratory determinants of the heterogeneity of HIV incidence at district level. All the variables considered had significant coefficients in the identified clusters except the male literacy rate, which was not significant in Shurugwi district. Negative values of DIFF of criterion indicates spatial variability while a positive value indicate no spatial variability (Table 4).

The percentage of permanently employed females showed a negative relationship with the HIV incidence in most of the districts. This means that the number of permanently employed females in Zimbabwe does not influence the incidence of HIV in most districts. The positive coefficients were very small with a maximum of 0.075 (Figure 3a). This includes districts such as Bulilima, Umguza, Bubi, Mangwe, Insiza and Umzingwane. The poverty severity index showed a negative association with HIV incidence in most of the districts except those in the southwestern region of the country (Bulilima, Gwanda, Matobo, Mangwe and Tsholotsho) including some parts of the identified cluster (Figure 3b). A few districts on the western part including Hwange, Lupane and Tsholotsho had the highest positive coefficients of the percentage of

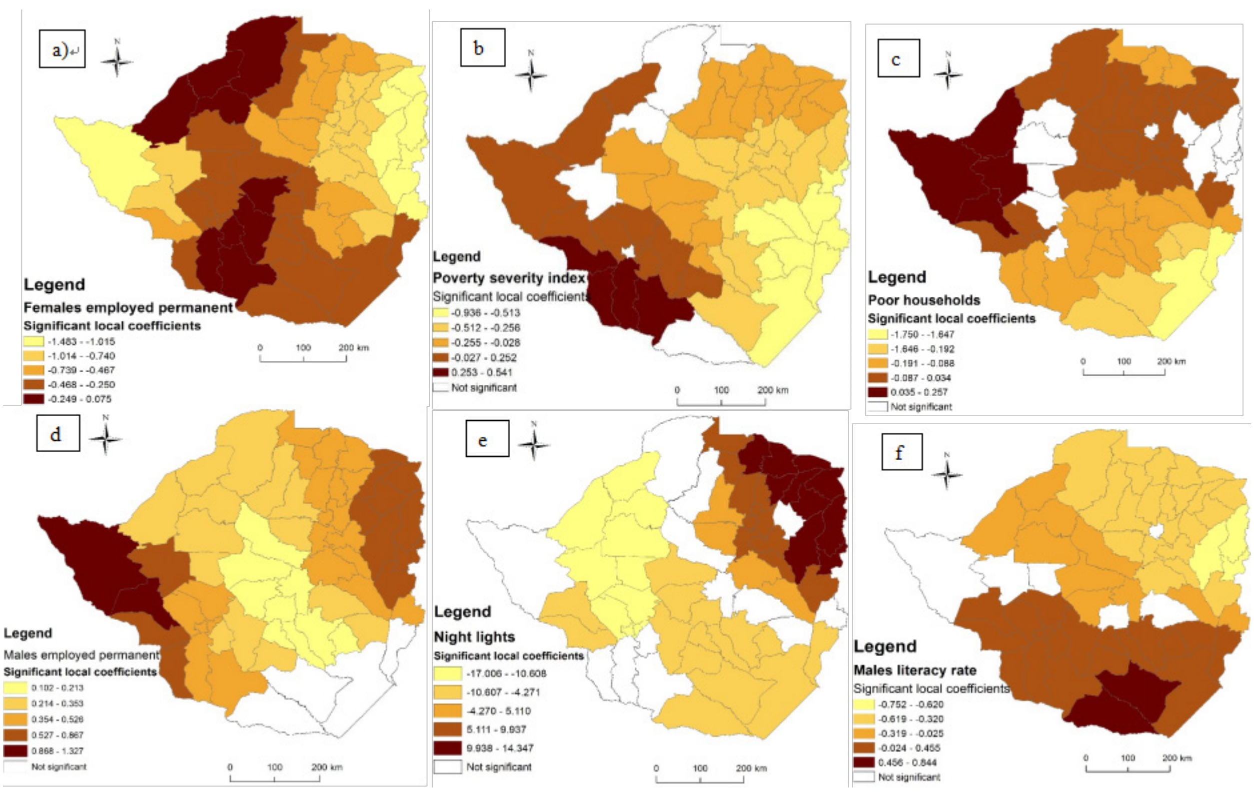


**Figure 3.** Spatial variation of the socio-economic factors considered in the current analysis of the spatial variation of HIV and AIDS incidence at district level in Zimbabwe a) Females employed permanently, b) Poverty severity index, c) Poor households d) Males employed permanently e) Night lights and f) Male literacy rate.



DOI: https://doi.org/10.30564/jgr.v4i3.3466

**Table 3.** Summary statistics of varying (local) coefficients in semi-parametric geographically weighted Poisson regression (s-GWPR) model for HIV and AIDS incidence in Zimbabwe

| Parameter | Minimum | 25 percentile | Median | 75 percentile | Maximum | DIFF of criterion |
|---|---|---|---|---|---|---|
| Intercept | -6.335 | -5.610 | -5.560 | -5.404 | -4.867 | -1335.443 |
| Poverty severity index | -0.936 | -0.329 | -0.171 | 0.017 | 0.541 | -916.352 |
| Female employed permanent | -1.483 | -0.882 | -0.525 | -0.277 | 0.075 | -715.616 |
| Male employed permanent | -0.062 | 0.235 | 0.412 | 0.525 | 1.327 | -672.155 |
| Poor households | -1.750 | -0.112 | -0.054 | -0.029 | 0.257 | -483.283 |
| Night Lights (Max value) | -0.272 | -0.102 | -0.007 | 0.095 | 0.204 | -162.327 |
| Male literacy rate | -0.752 | -0.465 | -0.148 | 0.189 | 0.844 | -600.431 |

[a]Negative values of DIFF of criterion indicate spatial variability; [b]Positive values of DIFF of criterion indicate non-spatial variability

poor households (Figure 3c). The percentage of permanently employed males had a positive association with HIV incidence with the highest coefficients observed in the southwestern districts (Hwange, Lupane, Tsholotsho and Bulilima districts). Moderate coefficients were noted to the northeastern districts of the country (Figure 3d). Nightlights, used as a proxy for local economic development, had the highest positive coefficients to the northeastern part of the country. Only Mangwe district to the southwestern part had a high and positive coefficient. This maximum was noted in the most likely cluster as well (Figure 3e). The male literacy rate had higher coefficients in the southern districts of the country with the highest rates in Beitbridge and Mwenezi, (Figure 3f).

## 4. Discussion

This study has shown that HIV incidences vary across the districts in Zimbabwe with the major cluster located in the rural districts as previously noted by Gwitira et al [35]. The socio-economic variables considered in this study showed geographical variation of associations between HIV incidences and all the socio-economic factors except the percentage of females employed which was constant across the study area. These associations were significant in most of the districts with their contribution either positive or negative. Therefore, we concur with Alves et al. [4] that the effects of some of exploratory variables of HIV incidences are not constant throughout a landscape, thereby opposing the assumptions in the global models. In this study we have shown the need for combining local and global variables to understand the spatial variation of HIV incidence since the s-GWPR outperformed other models.

Although it may be noted that AIDS may result in poverty, this disease may not be regarded as a disease of poverty. Our study has noted a relationship between gender and related economic inequalities and HIV incidence in Zimbabwe. We noted that the percentage of males permanently employed had high and positive coefficients in most of the districts in the country. This also applied to the economic activities as indicated by night-lights. This is in agreement with Gillespie et al. [36] who noted that higher incomes from males tend to be associated with higher HIV incidence while income inequality does show a strong association with HIV prevalence. This was also augmented by the night-light data, which is a useful tool to measure spatial economic activity over fine geographical areas in unmeasured economies such as Zimbabwe [37,38].

The percentage of females employed permanently had a negative relationship with HIV incidence. This was shown by negative coefficients in most of the districts and slightly small size of positive coefficients in a few districts. This may indicate that when women are permanently employed, they have the capacity to take care of themselves. They stop relying on men; are able to negotiate and stand for safer sex; and can adopt different HIV prevention methods. The economic dependence of women on their male partners may make it difficult for them to insist on safer sex (e.g., condom use) [8].

The percentage of poor households per district and poverty severity index showed mixed relationship with HIV incidences. We concur with the substantiation by Gillespie et al. [36] that poverty is a major driver of HIV and may exacerbate poverty. Wealth can be both negatively and positively associated with HIV infection depending on the livelihoods of the affected population. Poverty places individuals particularly women at greater risk of exposure to HIV as they end up engaging in transactional sex [39]. On a different note, Masvawure [40] noted that exchanging sex is also regarded as a 'high-status, successful modern subject' i.e., from well up individuals. This has also been linked to increased risk of HIV [41]. Similar to males employed permanently, male literacy rate showed a positive relationship with HIV and AIDS incidences in most of the districts in Zimbabwe. Instead of showing a protective sign, it seems male literacy is giving power to males to negotiate for whatever form of sex they want. This could increase the

HIV incidence. Xiong [42] highlighted that although the general impact of poverty on HIV/AIDS remains unclear, there is some evidence that HIV-related outcomes are more detrimental among those who are already poor.

This study also showed that the detection of flexible noncircular clusters of the HIV is complementary to using the Kulldorff's circular spatial scan statistic. The Tango and Takahashi's flexible spatial scan statistic used in this study also agreed with LISA as applied in ArcGIS10.4, except that Insiza district was considered as part of the more likely significant cluster in the former and not in the latter. This could be explained by the differences in the sensitiveness of these methods. Our study findings can be used for tailor making programmes targeting socio-economic issues to address the HIV incidence and prevalence. For example, women empowerment programmes through education and employment creation as well as place specific programmes targeting HIV programmes. These programmes should consider all socio-economic groups in the communities including youths and women and taking into consideration the complex relationships between socio-economic factors and HIV. The conventional view that educated and wealthy men can make wise decisions including safer sex should be challenged.

In this study we considered only key socio-economic variables related to HIV in Zimbabwe. The inclusion of other variables related to the control measures or intervention strategies at district level could also be considered in future studies. Our study contributes to the diversity of GIS and spatial analysis themes and methodologies in understanding the HIV dynamics in Zimbabwe. The GWPR results may be useful for public health stakeholders involved in reviewing local and regional policy and services. As noted in the current study, there is no universal agreement in the literature nor strong statistical evidence that poverty increases exposure to HIV. In line with Xiong [42] the mixed conclusions from literature indicates that HIV is a complex problem and it may not be appropriate to strictly define HIV as an infection driven by poverty [42]. As also highlighted by our study was cross-sectional and hence prone to the criticism of the limitation to infer the temporality of the associations [4].

## 5. Conclusions

HIV incidences and their association with socio-economic factors vary at local level. There is need to empower women as the percentage of permanently employed females showed a negative relationship with the HIV incidence in most of the districts. This could also be complemented by implementing programmes that may reduce the percentage of poor households across the districts. The results of this study can be used by different stakeholders including MOHCC and NGOs in the development of HIV intervention strategies at district level as opposed to the blanket strategies that are developed at national level. These interventions should target the identified socio-economic factors at district level so as reduce the HIV incidence. Theoretically and methodologically, our study demonstrates the usefulness of a geographical approach to the study of disease and, relatedly, the importance of (a) acknowledging the positionality and situatedness of one's knowledge [43-45], and (b) studying a given medical phenomenon across geographical scales, from the personal to the social [46-48].

## Data Availability

All data generated or analysed during this study are included in this manuscript.

## Compliance with Ethical Standards

Funding: The authors did not receive support from any organization for the submitted work.

Conflict of interest: The authors have no conflicts of interest to declare that are relevant to the content of this article.

Informed consent: There was no involvement of human participants. All the data used in this study was obtained from publicly available reports.

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ISSN 2630-5070