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Post-Flood Challenges to Polio Eradication in Pakistan

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ABSTRACT

This study aims to investigate the effect of flood on polio vaccination coverage among children aged 0-2 years in Pakistan, with a particular emphasis on the impact of floods on vaccination rates in both urban and rural areas, male and female, families of varying sizes, families with educated and uneducated heads, and the socio-economic status of households. The study utilized household-level data from the Pakistan Social and Living Standards Measurement surveys conducted between 2004-05 and 2014-15. Difference-in-Differences (DID) analysis and inverse probability of treatment weighting (IPTW) were employed, treating the flood as a quasi-natural experiment. The flood in 2010 in Pakistan disrupted polio vaccination coverage significantly; particularly in rural areas and among households led by uneducated parents. During the flood, 135 out of 1000 children aged 0-2 years were not fully vaccinated against poliovirus, and this number varied across different regions and family sizes with 171 fewer children per 1000 fully vaccinated during the flood in rural flooded areas. The adverse effects persisted for several years, with disparities observed based on parental education, gender, and household assets. Despite some recovery, the decline in polio immunization coverage remained significant in the years following the flood, especially in large families and impoverished households. Disparities based on gender, socioeconomic status, parental education, and family size were evident. Regardless of global efforts to combat polio, natural disasters like floods pose significant challenges to immunization programs, emphasizing the need for targeted interventions and improved disaster preparedness in vulnerable regions.

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1. Introduction

The climate crisis is exacerbating children's vulnerability to various threats, including cyclones, flooding, and vector-borne diseases, impacting their rights to health, education, and protection as per the United Nations Convention on the Rights of the Child (United Nations International Children's Emergency Fund, 2021). The Children's Climate Risk Index highlights that nearly one in six children are highly exposed to cyclones, one in seven to riverine flooding, one in ten to coastal flooding, and over one in four to vector-borne diseases, underscoring the need for prioritized action to safeguard their well-being and rights during and after natural disasters. Health interventions, particularly vaccinations, play a crucial role in enhancing economic well-being by improving school performance, productivity, and social functioning (Bärnighausen, Bloom, Cafiero-Fonseca, & O'Brien, 2014). Vaccinations offer extensive health, economic, and social benefits that extend far beyond the direct reduction of healthcare costs and disease burden; the vaccinations reduces illness and mortality rates, as well as improvements in social equity and economic productivity (Cadarette et al., 2023; Nandi & Shet, 2020). Despite offering these benefits to the society, the economic advantages of vaccination are often underrepresented in terms of economic evaluations and assessments. Which leads to underinvestment in the development of new vaccines; a gap that can be addressed through more comprehensive evaluations and expanded empirical research (Bärnighausen et al., 2014). Vaccines are beneficial to the population of low- and middle-income countries (LMICs) particularly because these can prevent medical expenses and reduce the incidence of catastrophic health expenditures (Nandi & Shet, 2020). Vaccination programs are not only cost-effective but also contribute to economic growth meaningfully by enhancing the productivity of workforce and supporting social and health equity. These further reduce the disease burden among the poorest populations and combat global health threats like antimicrobial resistance that may cause saving millions of lives and trillions of dollars globally (Nandi & Shet, 2020; Rodrigues & Plotkin, 2020). The economic benefits of vaccination are highlighted by Watts, Sim, Constenla, Sriudomporn, Brenzel, and Patenaude (2021) in their study covering the period from 2011 to 2020 that vaccines provided economic benefits is equivalent to 0.9% to 3.0% of GDP in LMICs (Watts et al., 2021). Since, interalia, the prevention of productivity loss due to deaths and disabilities from vaccine-preventable diseases (VPDs) founds the largest component of these benefits, therefore it emphasizes the importance of sustained investment in immunization programs to achieve significant economic gains (Watts et al., 2021).

Childhood vaccination is one of the essential components for promoting children's health and development. However, vaccine hesitancy, fueled by concerns over adverse reactions and mistrust, remains a significant barrier. This hesitancy effects the realization of children's right to health as outlined in the United Nations Convention (Ngo, Pemunta, Muluh, Adedze, Basil, & Agwale, 2020). The authors also identified factors such as rumors, suspicions, and conflicts exacerbate this issue, leaving some children vulnerable and underserved. In crisis-affected settings, such as those experiencing natural disasters, conflicts, and food shortages, populations face increased susceptibility to VPDs. Nearly half of the zero-dose children reside in such areas, highlighting the need for effective vaccine delivery strategies to mitigate the risk of infectious diseases and improve access to vaccinations (Allison et al., 2023). This is particularly relevant during and after floods, where disruptions to healthcare infrastructure can leave children behind in vaccination efforts, further endangering their health and development.

The World Health Organization (WHO) reported 199 polio cases in 2000 in Pakistan, representing a decrease from the 32 cases in 2007 (World Health Organization, 2023c). However, this progress was followed by a surge to 117 cases in 2008, and 89 cases in 2009. The situation worsened in 2010, a year marked by devastating floods, which led to a significant spike to 144 cases. Subsequent years witnessed a continuous rise, with 198 cases in 2011 and 306 cases in 2014. Notably, a correlation was observed between polio vaccination coverage, specifically the third doses, and the incidence of polio cases in Pakistan (World Health Organization, 2023c). According to the Pakistan Polio Eradication Programme (PPEP), as of October 2023, there has been a substantial improvement, with the number of wild poliovirus (WPV) polio cases in Pakistan dropping to 3, a remarkable reduction from the 20 cases reported in year 2022 (Pakistan Polio Eradication Programme, 2023). Pakistan, situated in a region prone to various natural disasters, faces significant impacts on public health during calamities such as floods (Abbas, Amjath-Babu, Kächele, & Müller, 2015; Raza, Khan, Ali, Hussain, & Narjis, 2021). Floods, such as those in Pakistan, disproportionately affect vulnerable populations, especially women and children, heightening their risks and vulnerabilities (Sadia, Iqbal, Ahmad, Ali, & Ahmad, 2016), disrupting essential services, such as immunization programs, and leading to delayed or missed vaccinations, exacerbating existing vulnerabilities and posing significant challenges to healthcare services (Sahoo, Negi, Patel, Mishra, Palo, & Pati, 2021). As of 9 November 2010, Pakistan reported 111 out of 180 Poliomyelitis (polio) cases from endemic countries, constituting 62% of the total, with the majority of new cases originating in flood-affected regions (Warraich, Zaidi, & Patel, 2011). Currently, there is a global effort to eliminate polio in various regions and achieve its worldwide eradication, defined as the permanent reduction of global infection incidences to zero (Ughasoro et al., 2023). The introduction of the inactivated poliovirus vaccine (IPV) in the 1950s marked a significant milestone in the battle against polio, paving the way for global initiatives such as the Global Polio Eradication Initiative (GPEI) in 1988, which led to a remarkable 99% reduction in global poliomyelitis cases by 1999, ultimately resulting in the eradication of one of the three wild poliovirus serotypes, serotype 2 (Bhutta, 2011). In developing countries such as Pakistan, the live-attenuated oral poliovirus vaccine (OPV), introduced in 1963, remains the primary choice due to its affordability, ease of oral administration, and superior ability to induce intestinal immunity compared to IPV (Orenstein & The Committee on Infectious Diseases, 2015).

Despite the substantial progress in immunization and vaccination achieved globally, substantial challenges still persist, particularly in developing countries like Pakistan. The journey towards polio eradication has been marred by multifaceted obstacles, including but not limited to religious, political, and socioeconomic barriers, conflicts, conspiracy theories, and vaccine hesitancy (Hussain, Boyle, Patel, & Sullivan, 2016; Mohammed et al., 2023; Rahim, Ahmad, & Abdul-Ghafar, 2022). In Pakistan—where only 66% of children aged 12-23 months are fully immunized—4% receive no immunizations and the rest have incomplete vaccinations (Jamal et al., 2020). Global efforts have made progress, with 84% of infants worldwide receiving three doses of the polio vaccine in 2022 (World Health Organization, 2023a). Despite the efforts of organizations like the WHO and the GPEI, challenges such as negative socioeconomic factors, conflicts, and geographical disparities hinder immunization completion, particularly in the flood-prone regions of Pakistan (Hussain et al., 2016). The devastating floods in 2010 and 2022 left millions people in Pakistan displaced, disrupted healthcare services, and underscored the need for comprehensive research on the intersection of natural disasters and healthcare delivery. The fight against various illnesses—exacerbated by inadequate clean water, sanitation, and damaged infrastructure—intensified in camps and areas, hindering nationwide polio immunization efforts due to challenges like rain and flooding (Ochani, Aaqil, Nazir, Athar, Ochani, & Ullah, 2022). The viral illness—characterized by acute paralysis, muscle weakness, and autonomic dysfunction, continues to haunt regions marked by inadequate sanitation and hygiene practices—spreads primarily through contaminated water via the feco-oral route (Shabbir et al., 2022). The WHO reported a surge in cases of Crimean Congo Hemorrhagic Fever, dengue fever, cholera, falciparum malaria, measles, and polio in flood-affected districts; with excessive rainfall and flooding served as breeding grounds for these diseases, reminiscent of the 2010 flooding crisis (Warraich, Zaidi, & Patel, 2011). The purpose of this study is to investigate the effect of the flood in 2010 on polio vaccination coverage among children aged 0-2 years in Pakistan. Pakistan is a nation where the polio virus remains a persistent threat despite significant resources being allocated to its eradication. The study's primary focus is on Pakistan's efforts to combat polio during a natural disaster, with a particular emphasis on the impact of floods on the vaccination of children aged 0-2 against polio. The research aims to scrutinize how floods disrupt polio vaccination rates in both the short and long term, with a specific differentiation between urban and rural areas, male and female children, families of varying sizes, families with educated and uneducated heads, as well as the socio-economic status of households, ranging from the poorest to the wealthiest.

2. Martials and Methods

2.1. Household level data

The data utilized for this study encompassed information regarding polio vaccination for children aged 0-2 years, as well as several key variables, such as children's ages, household size, and the highest education level of the head of the family (measured in years). Information about polio vaccination, this study relies on the vaccination data documented in the child's vaccination card. A child was regarded as completely immunized against polio if there was documentation confirming the receipt of all three doses of OPV (OPV 1, OPV 2, and OPV 3), regardless of whether the birth dose (OPV 0) had been administered. These data were sourced from the Pakistan Social and Living Standards Measurement (PSLM) surveys, conducted nationally every two years by the Pakistan Bureau of Statistics (PBS) from 2004-05 to 2014-15, spanning six survey waves (Pakistan Bureau of Statistics, 2023). The unit of observation for this analysis is children of age 0-2 years within households.

2.2. Delineating flood exposed and comparison households

To perform the Difference-in-Differences analysis, we examined both treatment (households affected by flooding) and control (households unaffected by flooding) groups. For children aged 0-2, we determined flood impact using data from two sources: MapAction (MapAction, 2010) and Critical Threats Project (Critical Threats Project, 2010). By combining geospatial data, we identified residences that were either flooded or not. The severity of the 2010 flood in different districts was classified by these sources into heavily, mildly, and non-affected categories. In our study, a household in district was considered flooded (assigned a value of 1) if it was either mildly or heavily affected by the 2010 flood; otherwise, it was labeled as non-flooded (assigned a value of 0). Utilizing this information, we established a treatment group of households consisting of 63 flooded districts and a comparison group of households comprising 52 districts unaffected by the flood, as detailed in the articles (Ahmed, 2018; Ahmed, Barkat, Ahmed, Tahir, & Nasir, 2022).

2.3. Data analysis strategy

We used a methodology similar to the studies (Ahmed, 2018; Ahmed et al., 2022), treating the flood scenario as a quasi-natural experiment. We applied a difference-in-differences (DID) framework and inverse probability of treatment weighting (IPTW). The analysis involved a regression model with fixed effects for district and year, represented by the equation:

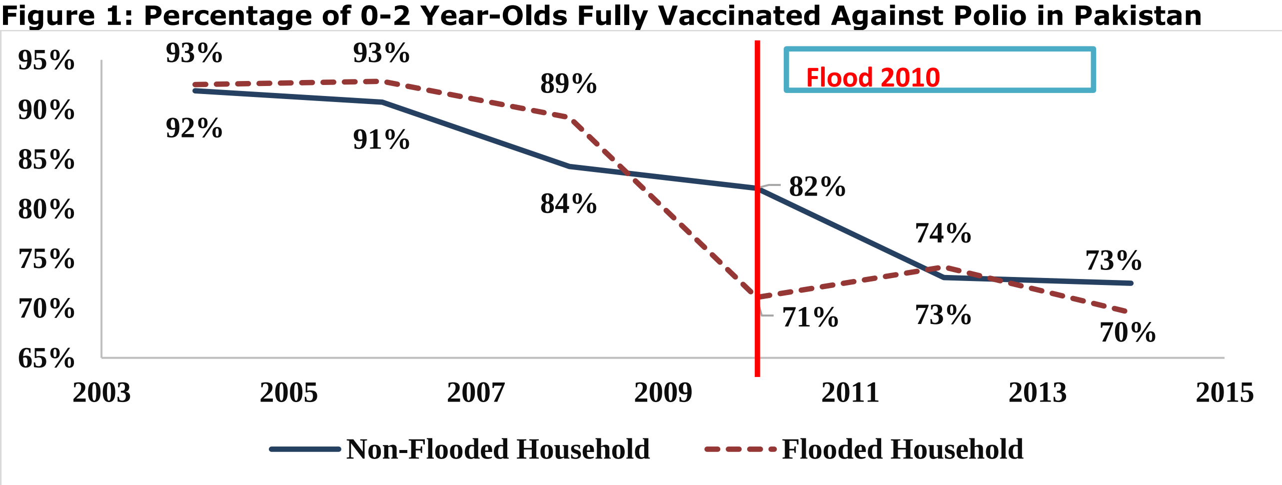
$$POL_{iht} = \alpha + \gamma_{dt} + \beta_1 Post11_t * FC_h + \beta_2 Post13_t * FC_h + \beta_3 Post15_t * FC_h + \varepsilon_{ihdt} ,$$

where, POL_{iht} represents the polio vaccination coverage of a child aged 0-2 years (denoted as i) in a household (denoted as h) surveyed in year (denoted as t) in Pakistan. Its value is 1 if the child had been vaccinated against the polio virus and 0 if not. This variable acts as the dependent variable for two types of regression: one for fully vaccinated children and another for children who received individual doses of the polio virus. A child was considered completely immunized against polio if there was documented evidence of receiving all three doses of OPV (OPV 1, OPV 2, and OPV 3) as stated in the child's vaccination card, irrespective of whether the birth dose (OPV 0) was administered. FC_h indicates children residing in households affected by floods. The dummy variables $Post11_t$, $Post13_t$, and $Post15_t$ denote observations during and after the flood in 2010-11, 2012-13, and 2014-15, respectively. The coefficients (β_1, β_2, β_3) indicate the impact of the flood on polio immunization coverage in flood-affected households compared to unaffected households during the flood, and in the second and fourth years after the flood respectively. The model also includes district-year fixed effects (γ_{dt}) to account for provincial-level shocks. Ordinary least squares (OLS) estimation with robust errors clustered at the primary sampling units (PSUs) level—and that is a village in rural setting while enumeration block in urban setting—was used for the analysis.

2.4. Pre-treatment trend equivalence

To confirm the validity of the DID method, we examined the parallel trends assumption by comparing polio vaccination rates among children aged 0-2 years in households affected by floods and those in non-flooded households prior to the 2010 flood. Figure 1 presents these trends, showing a slight disparity of 0-2% in polio immunization rates between non-flooded households in 2004-05 and 2006-07 (92% in 2004-05, 91% in 2006-07) and flooded households (93% in 2004-05, 93% in 2006-07). Additionally, there was a 5% difference between flooded and non-flooded households in 2008-09 before the flood. Despite these variances, consistent vaccination trends were observed between flooded and non-flooded households before the flood [see Figure 1]. Suddenly, a significant decline in vaccination coverage occurred during the flood, with a sharp 18% drop (from 89% to 71%) in flooded households, whereas non-flooded households experienced only a 2% decrease (from 84% to 82%). Subsequently, both groups nearly converged, reaching vaccination rates of 70-74% in 2013-14 and 2014-15.

Figure 1: Percentage of 0-2 Year-Olds Fully Vaccinated Against Polio in Pakistan



Source: PSLM Surveys (various issues) and author's own calculation

3. Results

3.1. Demographic characteristics

In this study, demographic characteristics were examined based on a dataset comprising 170,389 children aged 0-2 years residing in both rural and urban areas of Pakistan. Among these children, approximately 51% were male. The average age was 1.21 years in urban areas and 1.25 years in rural regions. Urban households had an average of 3.21 individuals, while rural households averaged 3.16 members. The average education level of the head of the residence was 4.70 years for the entire sample, with urban areas displaying a higher average of 6.52 years compared to 3.90 years in rural areas (see Table 1).

3.2. Flood impact on polio vaccination coverage

Between 2004 and 2015, the overall polio vaccination rate for children aged 0-2 years in Pakistan stood at 80%, as per data from children's vaccination cards and maternal recall (refer to Table 1). Notably, there was a slight disparity in vaccination rates between households affected by flooding and those that were not. In non-flooded households, 81% of children received all three doses of oral poliovirus vaccine (OPV1, OPV2, and OPV3), whereas in flooded households, the coverage was slightly lower at 79%. Prior to the flood (2004-2009), 88% of children in non-flooded households were fully vaccinated, while only 91% of children in flooded households received complete vaccination. After the flood (2010-2015), these percentages decreased to 76% for non-flooded households and 71% for flooded households, indicating a significant decline in vaccination coverage in both scenarios. Despite a 10%-point difference in polio vaccination coverage between urban (87%) and rural (77%) households, the data also revealed a more substantial decline in rural areas compared to urban ones (refer to Table 1). Specifically, during and after the flood (2010-2015), vaccination coverage for children aged 0-2 years in urban households decreased by 9 percentage points (from 92% to 83%), whereas it dropped by 18 percentage points (from 88% to 70%) in rural households. In non-flooded households, polio vaccination coverage decreased by 9 percentage points in urban areas (from 92% to 83%) and by 13 percentage points in rural areas (from 85% to 72%). In flooded households, the decrease was more significant, with a 12 percentage point drop in urban areas (from 94% to 82%) and a 22 percentage point drop in rural areas (from 90% to 68%). These findings, in conjunction with Figure 1, highlight a troubling decrease in polio vaccination coverage, particularly in rural areas, attributable to the flood.

Table 1: Summary statistics of Polio Vaccination of Children (0-2 years) – on record of vaccination card

	Overall (2004-2015)				**Before Flood (2004-2009)**			**During and after the flood (2010-2015)**		
	Obs.	Total	NFH	FH	Total	NFH	FH	Total	NFH	FH
Overall Sample										
Fully Immunized for Polio (%)	170,384	80	81	79	89	88	91	73	76	71
Male (%)	170,384	51	51	51	51	51	51	51	51	51
Age (in Years)	170,384	1.24	1.24	1.24	1.25	1.25	1.26	1.22	1.23	1.22
Household Members	170,384	3.18	3.05	3.30	3.83	3.63	4.06	2.70	2.57	2.81
Parents' Education (in years)	170,384	4.70	5.00	4.39	4.59	4.84	4.30	4.77	5.12	4.46
Urban Sample										
Fully Immunized for Polio (%)	51,955	87	88	87	92	92	94	83	83	82
Male (%)	51,955	51	51	52	52	52	52	51	51	52
Age (in Years)	51,955	1.21	1.21	1.22	1.22	1.22	1.23	1.20	1.20	1.21
Household Members	51,955	3.21	3.04	3.47	3.56	3.47	3.73	2.89	2.56	3.27
Parents' Education (in years)	51,955	6.52	6.61	6.37	6.32	6.37	6.22	6.70	6.89	6.48
Rural Sample										
Fully Immunized for Polio (%)	118,429	77	78	76	88	85	90	70	72	68

Male (%)	118,429	51	50	51	51	50	51	51	50	51
Age (in Years)	118,429	1.25	1.25	1.25	1.27	1.26	1.28	1.23	1.24	1.22
Household Members	118,429	3.16	3.06	3.25	3.98	3.76	4.19	2.63	2.58	2.67
Parents' Education (in years)	118,429	3.90	4.09	3.73	3.66	3.74	3.57	4.05	4.33	3.82

Notes: FH = Flooded households, NFH = Non-flooded households.
Data Source: PSLM Surveys (various issues) and author's own calculation.

3.3. Difference in differences (DiD) analysis

The 2010 flood in Pakistan had a significant detrimental impact on polio vaccination coverage, as indicated by children's vaccination records and maternal recall (see Table 2). During the flood, 135 out of 1000 children aged 0-2 years were not fully vaccinated against poliovirus. This number decreased to 45 within two years after the flood but then rose again to 74 within four years after the flood. This decline in polio immunization coverage was statistically significant at a 5% significance level. Notably, the adverse effects of the flood on full polio vaccination coverage were more severe in rural areas affected by the flood compared to urban areas, especially when compared to their non-flooded counterparts. Specifically, during the flood, 171 fewer children per 1000 in rural regions and 50 fewer children per 1000 in urban regions were fully vaccinated. The impact of the flood persisted in rural areas, with 60 and 65 fewer children fully vaccinated in the second and fourth years after the flood, respectively. In urban regions, the effect was less pronounced, with only 44 fewer children fully vaccinated in the year 2014-15 compared to their non-flooded counterparts. Additionally, the flood's impact on polio vaccination was more significant for female children than male children. During the flood, 140 and 129 fewer female and male children, respectively, out of 1000 remained unvaccinated for poliovirus in flooded households compared to their non-flooded counterparts. This effect persisted for both genders until the fourth year after the flood, with 65 fewer male children and 83 fewer female children out of 1000 remaining unvaccinated for poliovirus.

Table 2: Regression Results – Impact of the Flood 2010 on Polio Vaccination Coverage of Children (Aged 0-2 Years) in Pakistan

	Overall Sample	Region		Gender	
		Urban	Rural	Male Sample	Female Sample
Age 0-2 years					
FH x Post10-11	-0.135**	-0.050**	-0.171**	-0.129**	-0.140**
	(0.012)	(0.014)	(0.016)	(0.013)	(0.013)
FH x Post12-13	-0.045**	0.001	-0.060**	-0.051**	-0.039**
	(0.011)	(0.015)	(0.014)	(0.012)	(0.012)
FH x Post14-15	-0.074**	-.044*	-0.079**	-0.065**	-0.083**
	(0.043)	(0.020)	(0.013)	(0.012)	(0.012)
Observations	170,384	51,955	118,429	86,620	83,764
Age: Less than a year					
FH x Post10-11	-0.129**	-0.059*	-0.165**	-0.121**	-0.134**
	(0.017)	(0.026)	(0.023)	(0.022)	(0.023)
FH x Post12-13	-0.070**	-0.010	-0.098**	-0.058**	-0.080**
	(0.017)	(0.026)	(0.021)	(0.021)	(0.021)
FH x Post14-15	-0.089**	-0.059	-0.092**	-0.047*	-0.135**
	(0.016)	(0.032)	(0.020)	(0.021)	(0.021)
Observations	35,025	11,246	23,779	18,127	16,898
Age: One year					
FH x Post10-11	-0.1210**	-0.052**	-0.149**	-.0112**	-0.131**
	(.0131)	(0.016)	(0.018)	(0.016)	(0.016)
FH x Post12-13	-0.035**	0.009	-0.045**	-0.048**	-0.023
	(0.013)	(0.017)	(0.016)	(0.014)	(0.016)
FH x Post14-15	-0.059**	-0.027	-0.062**	-0.059**	-0.059**
	(0.012)	(0.023)	(0.015)	(0.015)	(0.015)
Observations	60,033	1,8381	41,652	30,497	29,536
Age: Two years					
FH x Post10-11	-0.145**	-0.043**	-0.189**	-0.142**	-0.146**
	(0.013)	(0.015)	(0.018)	(0.015)	(0.016)
FH x Post12-13	-0.041**	-0.001	-0.055**	-0.048**	-0.035*
	(0.012)	(0.017)	(0.016)	(0.014)	(0.015)

FH x Post14-15	-0.076**	-0.052*	-0.083**	-0.075**	-0.075**
	(0.013)	(0.023)	(0.015)	(0.015)	(0.015)
Observations	75,326	22,328	52,998	37,996	37,330

Note: Dependent Variable: Child vaccinated fully against all three doses of poliovirus (OPV 1, OPV 2, and OPV 3). Robust standard errors in parentheses, clustered at the primary sampling units (village in rural areas and enumeration blocks in urban areas) level. * p<0.05, ** p<0.01. Models estimated by OLS. District year dummies are included. Other Control Variables are age, number of residence members, and education level of head of family.
Data Source: PSLM surveys (various issues), PBS, Islamabad, Pakistan.

3.4. Age specific analysis

In our analysis of specific age groups, it was observed that the 2010 flood exerted a considerable influence on the vaccination rates among children under the age of one (referred to as age group 1), one-year-olds (age group 2), and two-year-olds (age group 3). Our findings indicated that, during the flood period, there were 129, 121, and 145 children, respectively, in these age groups residing in flooded households who remained unvaccinated against poliovirus, in stark contrast to their counterparts in non-flooded households (see Table 2). Particularly striking was the disparity in the impact between rural and urban areas. In rural regions, the effect was notably more pronounced, with 165, 149, and 189 fewer children in age groups 1, 2, and 3, respectively, receiving complete poliovirus vaccination in flooded areas compared to non-flooded areas. Conversely, urban areas witnessed 59, 52, and 43 fewer unvaccinated children in age groups 1, 2, and 3, respectively, in comparison to their non-flooded counterparts. Interestingly, the adverse effects in rural areas were not confined to the flood year; instead, they persisted into the second and fourth years following the flood. Specifically, in the second year, 98, 45, and 55 children in age groups 1, 2, and 3, respectively, remained unvaccinated, while in the fourth year, these numbers were 92, 62, and 83, respectively. It is pertinent to note that there were no discernible gender-based differences in terms of vaccination rates across these age groups; both male and female children were equally affected by the negative impact of the flood on vaccination rates.

3.5. Socioeconomic factors and flood-related polio vaccination

The investigation delved into the disparities in polio vaccination rates between households led by educated parents and those led by uneducated parents, both during and after the flooding incident. Amongst children from uneducated parent-led households in flood-affected areas, a significant decline in polio vaccination rates was observed over several years. Specifically, during the flood year, the rate plummeted to 151 per 1000 children, further dropping to 62 in the second year, and slightly recovering to 75 in the fourth year of the flood, as indicated in Table 3. Conversely, children from educated parent-led households exhibited rates of 93 during the flood year, with no substantial impact in the second year, registering at 74 in the fourth year of the flood. Upon closer examination of urban and rural regions, both educated and uneducated parent-led households experienced a considerable decrease in polio vaccination coverage in rural areas. However, the adverse effects of the flood were more pronounced for households led by uneducated parents, with rates of 182 and 133 respectively, in flooded areas, compared to their counterparts in non-flooded households during the flood year.

A comprehensive analysis of household assets, conducted through principal components analysis (PCA) for quintile categorization, revealed that children in the poorest households (lowest quintile) exhibited higher rates of non-immunization compared to their counterparts in the wealthiest households (highest quintile). Specifically, during the flood, 193 more children in the poorest households and 91 more children in the richest households in flooded areas remained unvaccinated against polio (see Table 3). Despite this significant disparity, the impact of immunization against poliovirus in the poorest households diminished after the flood year, while in the wealthiest households, the decline in vaccination persisted into the second and fourth years of the flood, with 54 and 90 children per 1000 remaining unvaccinated in flooded households. The influence of floods on immunization rates was notably substantial in rural households, especially in the poorest flooded households, where approximately 103 more children (207 for the first quintile and 104 for the fifth quintile) were unvaccinated compared to the wealthiest flooded households during the 2010 flood, relative to their counterparts in non-flooded areas.

The 2010 flood significantly impacted polio vaccination coverage, with discernible disparities across various family sizes and regions. Large families (comprising more than three members) experienced a higher rate of decline in polio vaccination coverage compared to small families (up to three members) in flood-affected households (see Table 3). In large families, vaccination coverage declined to 143 per 1000 children during the flood and persisted at 40-50 children levels in the subsequent years, in contrast to their counterparts in non-flooded households. Small families also experienced a severe effect, albeit to a lesser extent than large families; their child immunization coverage decreased to 118 per 1000 children in flooded households during the flood. Urban areas witnessed a nearly twofold reduction in full poliovirus immunization for large families (93) compared to small families (41). Rural households experienced a substantial decline in children's polio vaccination, with a 10-point difference between small and large families, registering at 155 and 165 respectively, in flooded households, relative to their counterparts in non-flooded rural households. The adverse impact of the flood on polio vaccination coverage persisted in flooded households for both types of families even after the second and fourth years of the flood.

Table 3: Flood Effect on Polio Vaccination Coverage of Children (aged 0-2 years) – Education, Asset Index, and Family Size

	Household Head's Education		**Household Asset Index**		**Household Family Size**	
	Uneducated	**Educated**	**Poor Household**	**Rich Household**	**Small Family**	**Large Family**
Overall Sample						
FH x Post10-11	-0.151**	-0.093**	-0.193**	-0.091**	-0.118**	-0.143**
	(0.013)	(0.014)	(0.027)	(0.016)	(0.012)	(0.028)
FH x Post12-13	-0.062**	-0.003	-0.031	-0.054**	-0.034**	-0.041*
	(0.012)	(0.013)	(0.024)	(0.015)	(0.012)	(0.018)
FH x Post14-15	-0.075**	-0.074**	-0.011	-0.090**	-0.065**	-0.048**
	(0.012)	(0.015)	(0.025)	(0.014)	(0.012)	(0.018)
Observations	126,371	44,013	33,911	32,714	112,346	58,038
Urban Areas						
FH x Post10-11	-0.056**	-0.044*	0.028	-0.077**	-0.041**	-0.093**
	(0.016)	(0.017)	(0.061)	(0.019)	(0.014)	(0.037)
FH x Post12-13	-0.006	0.013	0.077	-0.024	-0.005	0.028
	(0.018)	(0.018)	(0.061)	(0.019)	(0.015)	(0.028)
FH x Post14-15	-0.036	-0.052*	0.067	-0.064**	-0.061**	0.004**
	(0.024)	(0.023)	(0.075)	(0.022)	(0.023)	(0.029)
Observations	31,194	20,761	2,607	17,724	33,700	18,255
Rural Areas						
FH x Post10-11	-0.182**	-0.133**	-0.207**	-0.104**	-0.155**	-0.165**
	(0.017)	(0.023)	(0.029)	(0.026)	(0.016)	(0.038)
FH x Post12-13	-0.076**	-0.007	-0.036	-0.070**	-0.044**	-0.078**
	(0.015)	(0.020)	(0.025)	(0.022)	(0.015)	(0.023)
FH x Post14-15	-0.079**	-0.082**	-0.016	-0.087**	-0.065**	-0.065**
	(0.014)	(0.020)	(0.027)	(0.019)	(0.014)	(0.023)
Observations	95,177	23,252	31,304	14,990	78,646	39,783

Note: Dependent Variable: Children Fully Vaccinated with all three doses of poliovirus (OPV1, OPV2, OPV3). Uneducated = head of household having a degree below metric education; educated = head of household having a degree of metric and above education. Poor households = household and rich households = households in the first and fifth quintiles of the asset index, respectively, calculated using principal component analysis using the households' assets including iron, fan, sewing machine, radio, table/chair, watch clock, TV, cd player, refrigerator, air collar, air conditioner, computer, bicycle, motor cycle/ scooter, car/truck, and tractor. Small family = up-to three members in the household; large family=more than three members in the household. All other details remain consistent with those in Table 2, with the exception of variations in the family head's education level and the number of members in household excluded in their regression models for education and family size.

3.6. Robustness check and sensitivity analysis

To ensure the credibility of our findings and address potential biases, we conducted robustness checks and sensitivity analyses (see Table 4). We implemented two temporal and one spatial placebo experiments to validate our results. Firstly, hypothetical floods were assumed in 2006-07 and 2008-09, using household data from 2004-05 and 2008-09. The outcomes revealed that coefficients related to the pseudo-flood of 2006-07 or 2008-09 had no significant impact on the rate of full polio vaccination among children during and after the pseudo flood, corroborating the reliability of our primary analyses. Moreover, we performed a spatial placebo experiment on households unaffected by the 2010 flood. These households were randomly categorized into two pseudo groups: pseudo-flooded and pseudo-non-flooded households using the STATA 13 package. The analysis confirmed that the coefficients of interest remained insignificant, affirming that the adverse effects on child vaccination rates after the 2010 flood were specific to that event. An important limitation of our analysis pertains to the data on child poliovirus vaccination. We utilized both the child's vaccination data from the immunization records in the child vaccination card and maternal recall, considering that maintaining a vaccination card in developing countries is challenging, especially for uneducated families, despite the availability of free vaccinations and healthcare facilities. Floods can damage household belongings, including vaccination cards, and relying on maternal memory alongside child vaccination data could serve as a better proxy for assessing child vaccination. To address this potential bias, we tested whether child vaccination records alone could serve as an adequate proxy, excluding maternal memory. The results presented in Table 5 demonstrated a comparable effect of the 2010 flood on children's vaccination (based solely on records in the child's vaccination card) in flooded households compared to non-flooded households, supporting our primary analysis. Furthermore, we investigated the broader impact of disasters, including floods and earthquakes, in Pakistan from 2004 to 2015, utilizing data from the EM-DAT database (EM-DAT CRED, 2022). By running a regression of disaster-affected and unaffected households on child vaccination against poliovirus while controlling for other factors, we found that, on average, 48 per 1000 children remained unvaccinated against poliovirus due to floods and earthquakes during 2004-2015 in Pakistan. This further strengthens our conclusion that the adverse effects on child vaccination during the flood were specifically attributable to the 2010 flood itself. Additionally, we applied a data trimming approach (Lunt, 2014), limiting the analysis to the first and fifth centiles of propensity scores. Despite excluding a portion of observations (i.e., 4.01% for the first centile and 17.46% for the fifth centile), the regression results remained consistent with the main analysis, providing further support for the robustness of our findings.

Table 4: Robustness Check and Sensitivity Analysis

	Placebo Experiments			**Alternative Measures**		**Trimming**	
	Pseudo Flood in 2006-07	**Pseudo Flood in 2008-09**	**Spatial Placebo**	**Polio vaccination based on Records only**	**Floods and Earthquakes (2004-2015)**	**Trimming (1st Centile)**	**Trimming (5th Centile)**
FH x Post06-07	0.014*						
	(0.006)						
FH x Post08-09	0.009	0.002					
	(0.008)	(0.007)					
FH x Post10-11			0.002	-0.037**		-0.135**	-0.136**
			(0.0076)	(0.013)		(0.012)	(0.012)
FH x Post12-13			-0.003	-0.086**		-0.048**	-0.055**
			(0.007)	(0.012)		(0.011)	(0.011)
FH x Post14-15			0.004	-0.038**		-0.077**	-0.083**
			(0.0075)	(0.012)		(0.011)	(0.012)
FH x Post-disaster					-0.048**		
					(0.005)		
Observations	71,614	71,614	85,812	157,561	170,384	163,540	140,628

Note: Outcome Variable: Percentage of Children Fully Vaccinated with all three doses of poliovirus (OPV1, OPV2, OPV3). All other regression specifications remain consistent with those outlined in Table 2.

4. Discussion

The persistent challenge of polio in Pakistan, one of the last two countries (the other being Afghanistan) with endemic poliovirus, necessitates a deep understanding of the factors hindering its eradication efforts. In 2021, Pakistan made significant strides by reducing polio cases to a mere one, a remarkable achievement attributed to intensified vaccination efforts (World Health Organization, 2023b). This success, however, contrasts sharply with the 2020 outbreak fueled by low immunization rates, lack of immunity, poor sanitation, and malnutrition, primarily in regions affected by the cVDPV2 strain. Over the past decade, Pakistan's experience with polio cases has exhibited a fluctuating pattern. In 2009, the country reported 89 cases, and this number rose to 144 in 2010, followed by a further increase to 198 cases in 2011 (Pakistan Polio Eradication Programme, 2023; World Health Organization, 2023c). The incidence remained high, with 141 cases in 2013 and a significant spike to 360 cases in 2014. However, cases plummeted to 20 in 2016, 8 in 2018, and 22 in 2019. Unfortunately, there was a sudden increase to 135 cases in 2020. The initial surge in 2010 was seemingly linked to reduced immunization rates after the devastating floods that year, which caused significant damage to health facilities. The second surge in 2020 was likely due to the disruptions caused by the COVID-19 pandemic and associated lockdown measures, which severely impacted immunization efforts.

Eradicating polio in Pakistan has proven challenging due to various obstacles. Inter alia, these obstacles include inconsistent and poor quality of immunization campaigns, the inability to reach children in certain areas due to conflicts and natural disasters like floods, weak routine immunization services, a fragile polio eradication program, and parental resistance to vaccinate their children (Khowaja, Khan, Nizam, Omer, & Zaidi, 2012; Nishtar, 2010; Shah et al., 2011). Among these challenges, floods stand out as a significant contributor to the spread of the polio virus due to their negative impact on vaccination coverage. The 2010 flood in Pakistan, for instance, caused substantial damage to public health facilities—with up to 11% of facilities in the hardest-hit provinces being damaged or destroyed. The flood in 2010 resulted in an estimated loss of PKR 4,222 million (US$ 49.67 million) and disrupted healthcare services—with 5.3% of the 9,271 health facilities nationwide being partially damaged or completely ruined (Asian Development Bank, Government of Pakistan, & World Bank, 2010). This study shed light on the complex interplay between natural disasters, socioeconomic factors, and polio vaccination rates in Pakistan—with a specific focus on the effect of devastating flood-2010 on child immunization. The observed decline in polio vaccination coverage during and after the flood period in this study highlights the vulnerability of healthcare infrastructure and immunization programs in the face of environmental catastrophes. Our study substantiates existing literature by highlighting the challenges faced by polio eradication efforts in Pakistan, elucidating the intricate dynamics that exacerbate the persistence of this infectious disease in certain districts of Pakistan.

The drastic reduction in polio vaccination coverage during the 2010 flood observed in this study aligns with previous research that emphasizes the susceptibility of immunization initiatives to disruptions caused by natural disasters. The damage inflicted upon healthcare facilities during the flood—coupled with logistical challenges in reaching affected areas—led to a substantial reduction in vaccination rates. This decline was particularly pronounced in rural regions where the confluence of limited access to healthcare, parental resistance, and the adverse effects of the flood created a perfect storm impeding immunization efforts. The persistence of this decline in subsequent years highlights the long-lasting repercussions of such disasters on healthcare delivery systems. Furthermore, our study also finds the role of socioeconomic disparities that exacerbated the adverse effects of the flood on polio vaccination rates in Pakistan. For example, children from households led by uneducated parents in the flooded areas experienced a more substantial decline in vaccination coverage compared to those from educated parent-led households in the flooded areas. Also, the effects of household assets and family size on vaccination rates further elucidates the intricate web of factors that contributed to disparities in the polio immunization during and after the flood. Large families—particularly in rural areas—faced a disproportionate impact that suggest the need for targeted interventions tailored to the specific needs of vulnerable populations. The robustness checks and sensitivity analyses further reinforce the credibility of the findings of this study. We also tested the specificity of the adverse effects observed during and after the 2010 flood by implementing temporal and spatial placebo experiments.

5. Conclusions

This study investigated the challenges faced by polio eradication efforts in Pakistan during and after natural disasters and highlights the multifaceted nature of obstacles that hinder immunization initiatives in polio-prone countries. A holistic approach—that encompasses improved healthcare infrastructure, targeted interventions for vulnerable populations, and enhanced disaster preparedness measures—requires to address these challenges. The findings of this study suggest that policymakers and healthcare professionals should develop informed strategies to mitigate the impact of natural disasters on polio vaccination and advance the goal of eradicating this debilitating disease in Pakistan. Only through targeted and evidence-based interventions can hope Pakistan to overcome the challenges posed by natural disasters and can eradicate polio successfully and safeguard the health and well-being of its youngest citizens.

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