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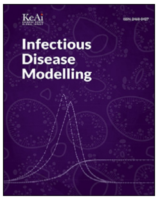

HCV transmission model with protection awareness in an SEACTR community

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ABSTRACT

Background: Hepatitis C virus (HCV) is a bloodborne virus that causes both acute and chronic hepatitis with the severity from a mild illness to liver cirrhosis and cancer. As one of the major infectious diseases in China, the monthly surveillance data from the Fujian Provincial Center for Disease Control and Prevention shows the increasing tendency from 2004 to 2011, the stable tendency from 2012 to 2016, and the declining tendency from 2017 to 2022. The 2004–2022 HCV infection tendency of Fujian Province is affected by nation-wide main control measures of Chinese government, because no control measures for HCV are modified from 2020 to 2022 during the prevalence of COVID-19 in Fujian Province.

Methods: The SEACTR (the susceptible, the exposed, the acutely infected, the chronically infected, the treated, the recovered) models with protection awareness are proposed. The next generation matrix method is used to compute basic reproduction number of toy model and dynamic analysis method is used to produce stochastic reproduction number of modified model. The least squares method and toy model are used to perform the optimal fitting against the monthly surveillance data. The positive preserving truncated Euler-Maruyama method is applied in modified model for the positivity of numerical simulations.

Results: The optimal fitting is performed using the monthly surveillance data provided by the Fujian Provincial Center for Disease Control and Prevention from 2004 to 2022. The sensitivities of protection efficiency and conversion rate to basic reproduction number and stochastic reproduction number are analyzed. The reproduction numbers and HCV infection scale with measures (single-measure, double-measure, triple-measure, and none-measure) are compared using toy model and modified model. The impacts of protection efficiency and conversion rate on exposed population, acutely infected population, chronically infected population, and treated population are analyzed. The tendency

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predictions for infected population and treated population in Fujian Province from 2023 to 2035 are conducted.

Conclusions: The HCV infection scale mainly depends on both protection efficiency and conversion rate, in which protection efficiency is the most important contributor. The reproduction numbers show the declining tendencies by phases, which indicate that the prevention and control of HCV in Fujian Province has achieved a remarkable achievement. The 2023–2035 tendency predictions of HCV infection scale in Fujian Province grow slowly due to approximately 19–109 monthly infections. The overall HCV growth tendency of Fujian Province is consistent with the nation-wide elimination objective.

1. Introduction

Hepatitis C virus (HCV) is a significant viral pathogen that affects the liver of human beings with global public health implications, and it is the leading cause of hepatitis, cirrhosis, and hepatocellular carcinoma worldwide. The primary transmission routes of HCV include the contacts with blood and bodily fluids of the infectious individuals. The HCV infection usually experiences the exposed phase, the acute phase and the chronic phase, and often leads to long-term liver damage such as liver cirrhosis and cancer. The exposed infections and acute infections are asymptomatic in the very early days and are hard to detect at early diagnosis with the silent spreading in the community. The majority of the chronic infections are symptomatic and are treated with direct-acting antiviral medicines (DAAs) in hospitals.

The effective prevention measures of HCV include the enhancement of public awareness, the appropriate use of healthcare injections, and safe sex with condoms. The impacts of protection awareness on the transmission dynamics have been investigated in some infectious diseases. For instance, Zhang and Xu (2017) focused on the susceptible population with protection awareness in an HCV model and analyzed the stability and persistence of the equilibrium points. Ma and Ma (2022) considered the reduction of the contact rate between susceptible population and HBV infected population by enhancing public health promotion activities. Khan et al. (2019) utilized education and media activities as the control measure to raise community awareness and to reduce HBV transmission. These studies revealed that the enhancement of protection awareness for the public effectively reduced the infectious disease transmission. Recently, Cui et al. (2020) adopted the SICR model and considered bilinear incidence rate to obtain the global stability of HCV. Later, Wang et al. (2020) used Cui's model and explored the epidemiological features of HCV in six districts of Xiamen City from 2004 to 2018, and also predicted the transmissibility of HCV.

The mathematical models with protection awareness have provided valuable insights into the transmission dynamics. Especially, the models with fluctuations could offer more comprehensive understanding towards the uncertainty in the real world. For instance, Zhai et al. (2023) examined the impacts of protection awareness among susceptible population within an HIV/AIDS stochastic model, and highlighted the importance of public education against the spread of HIV/AIDS. Liu and Guo (2024) investigated a stochastic within-host HCV model to explore the phenomena of unexpected relapse and recovery in HCV infected population. Qi et al. (2023) modified Cui's model by considering exposed population and nonlinear incidence rates to obtain the conditions of ergodic stationary distribution and stochastic extinction. Rajasekar et al. (2022) found that the fluctuations of key parameters for chronically infected population could dictate the persistence or extinction of HCV.

The investigation by using mathematical models becomes one of the most effective approaches when an epidemic course is studied. Especially, the scenario investigation and tendency prediction of infectious diseases play the vital roles in the recent studies (Lan et al., 2024; Chen et al., 2024; Zhai et al., 2023; Wang et al., 2024; Wei et al., 2023). However, the HCV model with protection awareness is less discussed in the recent literature. Therefore, this study aims to establish the SEACTR models with protection awareness and detects the impacts of protection awareness and the fluctuations, further conducts scenario investigation and tendency prediction for HCV in Fujian Province.

2. Methods

2.1. Data source and control measure

The monthly surveillance data of HCV infections for Fujian Province (January 2004–December 2022) are provided by Fujian Provincial Center for Disease Control and Prevention (i.e., Fujian CDC). It is important to point out that the monthly surveillance data do not include the awareness delay (i.e., the delay between the date of the first infection and the date of the first confirmation). However, the awareness delay plays the vital roles when infection scale is concerned in (Lan et al., 2024; Chen et al., 2024; Wei et al., 2023). Let the average incubation period of HCV be two months (Chinese Society of Hepatology, Chinese Medical Association, 2004, 2019). The awareness delay of HCV is taken as two months for the further investigation. Moreover, the nation-wide control measures of HCV were implemented by the Chinese government aiming at interrupting the transmission chains (Chinese Society of Hepatology, Chinese Medical Association, 2004; National Health Commission of the People' Republic of China, 2010; The State Council of the People's Republic of China, 2017), promoting the use of the effective drugs (Chinese Society of Hepatology, Chinese Medical Association, 2004, 2019) and making the effective drugs of HCV on the list of National Healthcare Security Administration (China Liver Health, 2022). The monthly incidence is calculated by monthly infection scale and yearly total population in Fujian Province. The yearly total population of Fujian Province is collected from the Fujian Statistical Yearbook in 2003 (Fujian Provincial Bureau of Statistics, 2023).

2.2. Model formulation

2.2.1. Toy model

We are motivated by the recent study (Wang et al., 2025) and assume that the total population of HCV is separated into eight compartments: S_u, the susceptible population without protection awareness; S_a, the susceptible population with protection awareness; E, the number of the exposed population; A and C, the numbers of acutely infected population and chronically infected population; T, the number of treated population; R_1 and R_2, the numbers of self-cured population and cured population respectively. Therefore, we propose an SEACTR model with flow chart in Fig. 1. The SEACTR model is written with $\beta(E,A,C)=(1-k_e)\beta_e E(t)+(1-k_a)\beta_a A(t)+(1-k_c)\beta_c C(t)$ as follows:

$$\begin{cases}\dot{S}_u(t)=\Lambda-\beta_e S_u(t)E(t)-\beta_a S_u(t)A(t)-\beta_c S_u(t)C(t)-\lambda S_u(t)-\mu S_u(t),\\ \dot{S}_a(t)=\lambda S_u(t)-\beta(E,A,C)S_a(t)-\mu S_a(t),\\ \dot{E}(t)\ =\beta(E,A,C)S_a(t)+(\beta_e E(t)+\beta_a A(t)+\beta_c C(t))S_u(t)-\nu E(t)-\zeta E(t)-\mu E(t),\\ \dot{A}(t)\ =\zeta E(t)-\delta A(t)-\mu A(t),\\ \dot{C}(t)\ =\alpha\delta A(t)-\varepsilon C(t)-\eta C(t)-\mu C(t),\\ \dot{T}(t)\ =\varepsilon C(t)-\gamma T(t)-\mu T(t),\\ \dot{R}_1(t)=\nu E(t)+(1-\alpha)\delta A(t)-\mu R_1(t),\\ \dot{R}_2(t)=\gamma T(t)-\mu R_2(t),\end{cases}\tag{1}$$

here, Λ is the constant recruitment rate; β_e, β_a, β_c are the transmission rates of exposed population, acutely infected population and chronically infected population, respectively; λ is the conversion rate from the susceptible population without protection awareness to the susceptible population with protection awareness through education and publicity; k_e, k_a, k_c are the protection efficiencies for exposed population, acutely infected population and chronically infected population; ν is the rate of self-healing for exposed population; $1/\zeta$ represents the average time removing out from exposed population to acutely infected population; $1/\delta$ represents the average time removing out from acutely infected population; α is the transfer proportion from acutely infected population to chronically infected population; ε is the transfer proportion from chronically infected population to treated population; η is the induced-death rate of chronically infected population; $1/\gamma$ denotes the average treatment time; μ is the natural death rate of the total population.

2.2.2. Modified model

Epidemic models with fluctuations provide more comprehensive understanding towards the uncertainty in reality. For instance, some epidemic models have considered the impacts of the fluctuations (Wu & Wei, 2022; Wei et al., 2021; Zhong et al., 2024; Li et al., 2022; Liu & Wei, 2022; Zhai et al., 2023), in which the reproduction number and stability of epidemic model with fluctuations alter. We are motivated by the previous contributions, and assume that the environmental noises are proportional to S_u, S_a, E, A, C, T, R_1 and R_2, then toy model (1) turns into modified model (2) as follows:

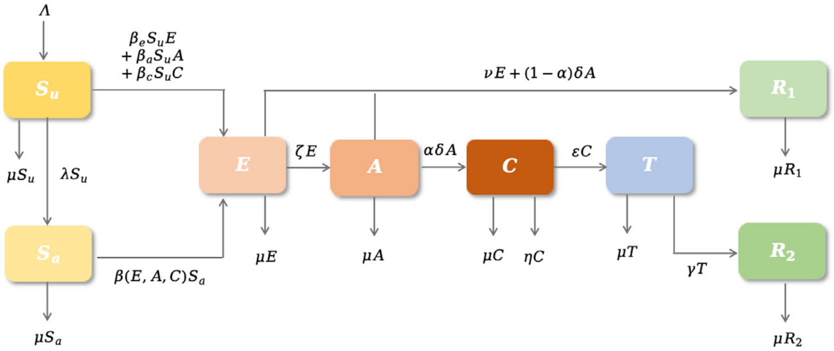

Fig. 1. Transfer mechanism of the SEACTR model.

$$\begin{cases} \mathrm{d}S_u(t) = [\Lambda - \beta_e S_u(t)E(t) - \beta_a S_u(t)A(t) - \beta_c S_u(t)C(t) - \lambda S_u(t) - \mu S_u(t)]\mathrm{d}t + \sigma_1 S_u(t)\mathrm{d}B_1(t), \\ \mathrm{d}S_a(t) = [\lambda S_u(t) - \beta(E,A,C)S_a(t) - \mu S_a(t)]\mathrm{d}t + \sigma_2 S_a(t)\mathrm{d}B_2(t), \\ \mathrm{d}E(t) = [\beta(E,A,C)S_a(t) + (\beta_e E(t) + \beta_a A(t) + \beta_c C(t))S_u(t) - \nu E(t) - \zeta E(t) - \mu E(t)]\mathrm{d}t + \sigma_3 E(t)\mathrm{d}B_3(t), \\ \mathrm{d}A(t) = [\zeta E(t) - \delta A(t) - \mu A(t)]\mathrm{d}t + \sigma_4 A(t)\mathrm{d}B_4(t), \\ \mathrm{d}C(t) = [\alpha\delta A(t) - \varepsilon C(t) - \eta C(t) - \mu C(t)]\mathrm{d}t + \sigma_5 C(t)\mathrm{d}B_5(t), \\ \mathrm{d}T(t) = [\varepsilon C(t) - \gamma T(t) - \mu T(t)]\mathrm{d}t + \sigma_6 T(t)\mathrm{d}B_6(t), \\ \mathrm{d}R_1(t) = [\nu E(t) + (1-\alpha)\delta A(t) - \mu R_1(t)]\mathrm{d}t + \sigma_7 R_1(t)\mathrm{d}B_7(t), \\ \mathrm{d}R_2(t) = [\gamma T(t) - \mu R_2(t)]\mathrm{d}t + \sigma_8 R_2(t)\mathrm{d}B_8(t), \end{cases} \tag{2}$$

where $B_i(t)$ are mutually independent standard Brownian motions defined on a complete probability space $\{\Omega, \mathcal{F}, \{\mathcal{F}_t\}_{t\geqslant 0}, \mathbb{P}\}$ with a filtration $\{\mathcal{F}_t\}_{t\geqslant 0}$ satisfying the usual conditions (i.e., it is increasing and right continuous, while $\mathcal{F}_0$ contains all $\mathbb{P}$-null sets); σ_i are the intensities of white noises for i = 1, 2, 3, 4, 5, 6, 7, 8.

2.3. Simulation method

2.3.1. Parameter estimation by least squares method

The parameter estimation plays a key role in determining epidemiological indices and characteristics. The least squares method is employed to ensure the minimum loss between the simulations and the surveillance data as investigated in (Chen et al., 2024; Lan et al., 2024; Li et al., 2024; Wang et al., 2024, Wei et al., 2024). Here, we use least squares method to estimate the main parameters of toy model (1) in Table 1.

2.3.2. Positive preserving truncated Euler-Maruyama method

The positive preserving truncated Euler-Maruyama method (PPTEM method) is a numerical method, and modifies the truncated Euler-Maruyama method, which is applied to the models with fluctuations for guaranteeing the positivity of numerical solution. Here, the PPTEM method is applied in modified model (2) to derive sample paths as performed in (Mao et al., 2021; Wang et al., 2024; Zhai et al., 2023).

2.4. Reproduction number

2.4.1. Basic reproduction number

The toy model (1) gives HCV-free equilibrium point $P_0 = \left(\frac{\Lambda}{\lambda+\mu}, \frac{\lambda\Lambda}{(\lambda+\mu)\mu}, 0, 0, 0, 0, 0, 0\right)$. Let $\mathcal{F}$ be the set of compartments E, A, C, T, and $\mathcal{V} = \mathcal{V}^- - \mathcal{V}^+$, in which $\mathcal{V}^-$ is the transfer rate of the individuals moving out from four compartments, $\mathcal{V}^+$ is the transfer rate for the individuals entering into four compartments by all other means. Then, we write down the following expressions:

Table 1
Main parameter values of HCV in Fujian Province from 2004 to 2022.

Parameter	Value	Period (Start-End) [a]	Source	Parameter	Value	Period (Start-End) [a]	Source
Λ	3.8227×10^4	2003–11 - 2022–12	FBS [b]	k_e	0.3000	2003–11 - 2022–12	Fitted
β_e	9.9943×10^{-9}	2003–11 - 2004–04	Fitted	k_a	0.3500	2003–11 - 2022–12	Fitted
β_e	9.7087×10^{-9}	2004–05 - 2010–09	Fitted	k_c	0.4000	2003–11 - 2022–12	Fitted
β_e	8.5665×10^{-9}	2010–10 - 2017–10	Fitted	ζ	0.5000	2003–11 - 2022–12	Fitted
β_e	7.9954×10^{-9}	2017–11 - 2022–12	Fitted	ν	0.1950	2003–11 - 2022–12	Fitted
β_a	7.7099×10^{-9}	2003–11 - 2004–04	Fitted	δ	0.1667	2003–11 - 2022–12	WHO [b]
β_a	5.7110×10^{-9}	2004–05 - 2010–09	Fitted	α	0.7000	2003–11 - 2022–12	WHO [b]
β_a	4.6259×10^{-9}	2010–10 - 2017–10	Fitted	ε	0.2000	2003–11 - 2019–12	Fitted
β_a	4.2833×10^{-9}	2017–11 - 2022–12	Fitted	ε	0.3000	2020–01 - 2022–12	Fitted
β_c	6.5677×10^{-9}	2003–11 - 2004–04	Fitted	η	2.0000×10^{-4}	2003–11 - 2022–12	Fitted
β_c	4.5688×10^{-9}	2004–05 - 2010–09	Fitted	γ	0.2222	2003–11 - 2021–12	Fitted
β_c	3.7122×10^{-9}	2010–10 - 2017–10	Fitted	γ	0.2500	2022–01 - 2022–12	Fitted
β_c	2.5700×10^{-9}	2017–11 - 2022–12	Fitted	μ	4.9379×10^{-4}	2003–11 - 2022–12	FBS [c]
λ	0.2000	2003–11 - 2022–12	Fitted	–	–	–	–

[a] 2003–11 is for YYYY-MM with Y (year) and M (month).
[b] WHO is World Health Organization in (World Health Organization, 2024).
[c] FBS is Fujian Provincial Bureau of Statistics in (Fujian Provincial Bureau of Statistics, 2023).

$$\mathcal{F}=\begin{pmatrix}((1-k_e)S_a+S_u)\beta_eE+((1-k_a)S_a+S_u)\beta_aA+((1-k_c)S_a+S_u)\beta_cC\\0\\0\\0\end{pmatrix},\quad \mathcal{V}=\begin{pmatrix}\nu E+\zeta E+\mu E\\-\zeta E+\delta A+\mu A\\-\alpha\delta A+\varepsilon C+\eta C+\mu C\\-\varepsilon C+\gamma T+\mu T\end{pmatrix},$$

the corresponding Jacobian matrices at HCV-free equilibrium point P_0 are followed:

$$F=\begin{pmatrix}\frac{\Lambda\beta_e(\mu+\lambda(1-k_e))}{(\lambda+\mu)\mu} & \frac{\Lambda\beta_a(\mu+\lambda(1-k_a))}{(\lambda+\mu)\mu} & \frac{\Lambda\beta_c(\mu+\lambda(1-k_c))}{(\lambda+\mu)\mu} & 0\\ 0&0&0&0\\0&0&0&0\\0&0&0&0\end{pmatrix},$$

$$V=\begin{pmatrix}\nu+\zeta+\mu & 0 & 0 & 0\\ -\zeta & \delta+\mu & 0 & 0\\ 0 & -\alpha\delta & \varepsilon+\eta+\mu & 0\\ 0 & 0 & -\varepsilon & \gamma+\mu\end{pmatrix}.$$

So, basic reproduction number of toy model (1) is spectral radius of the matrix FV^{-1}. That is,

$$\mathcal{R}_0=\mathcal{R}_0^e+\mathcal{R}_0^a+\mathcal{R}_0^c, \tag{3}$$

where

$$\mathcal{R}_0^e=\frac{\Lambda\beta_e(\mu+\lambda(1-k_e))}{(\lambda+\mu)\mu(\nu+\zeta+\mu)},\ \mathcal{R}_0^a=\frac{\Lambda\beta_a\zeta(\mu+\lambda(1-k_a))}{(\lambda+\mu)\mu(\nu+\zeta+\mu)(\delta+\mu)},\ \mathcal{R}_0^c=\frac{\Lambda\beta_c\alpha\delta\zeta(\mu+\lambda(1-k_c))}{(\lambda+\mu)\mu(\nu+\zeta+\mu)(\delta+\mu)(\varepsilon+\eta+\mu)}.$$

2.4.2. Stochastic reproduction number

By dynamic analysis method, the recent study (Wang et al., 2025) derives stochastic reproduction number $\mathcal{R}_0^s$ of modified model (2), which is written as follows:

$$\mathcal{R}_0^s=\mathcal{R}_0^{s-e}+\mathcal{R}_0^{s-a}+\mathcal{R}_0^{s-c}, \tag{4}$$

where

$$\mathcal{R}_0^{s-e}=\frac{\Lambda\beta_e\left(\mu+\frac{1}{2}\sigma_2^2+\lambda(1-k_e)\right)}{\left(\lambda+\mu+\frac{1}{2}\sigma_1^2\right)\left(\mu+\frac{1}{2}\sigma_2^2\right)\left(\nu+\zeta+\mu+\frac{1}{2}\sigma_3^2\right)},$$

$$\mathcal{R}_0^{s-a}=\frac{\Lambda\beta_a\zeta\left(\mu+\frac{1}{2}\sigma_2^2+\lambda(1-k_a)\right)}{\left(\lambda+\mu+\frac{1}{2}\sigma_1^2\right)\left(\mu+\frac{1}{2}\sigma_2^2\right)\left(\nu+\zeta+\mu+\frac{1}{2}\sigma_3^2\right)\left(\delta+\mu+\frac{1}{2}\sigma_4^2\right)},$$

$$\mathcal{R}_0^{s-c}=\frac{\Lambda\beta_c\alpha\delta\zeta\left(\mu+\frac{1}{2}\sigma_2^2+\lambda(1-k_c)\right)}{\left(\lambda+\mu+\frac{1}{2}\sigma_1^2\right)\left(\mu+\frac{1}{2}\sigma_2^2\right)\left(\nu+\zeta+\mu+\frac{1}{2}\sigma_3^2\right)\left(\delta+\mu+\frac{1}{2}\sigma_4^2\right)\left(\varepsilon+\eta+\mu+\frac{1}{2}\sigma_5^2\right)}.$$

2.5. Initial value and parameter value

By the Fujian Statistical Yearbook in 2003 (Fujian Provincial Bureau of Statistics, 2023) and 2004–2022 monthly surveillance data from the Fujian CDC, the initial values of HCV are set as $S_u(0)=22,062,568$, $S_a(0)=12,957,342$, $E(0)=90$, $A(0)=0$, $C(0)=0$, $T(0)=0$, $R_1(0)=0$, $R_2(0)=0$. Meanwhile, some parameter values are given in Table 1, others are estimated by toy model (1) and least squares method.

3. Results

3.1. Optimal fitting

The optimal fitting HCV in Fujian Province is performed using of toy model (1) and least squares method in Fig. 3, which is consistent with the 2004–2022 monthly surveillance data from the Fujian CDC in Fig. 2. Using of modified model (2) and PPTEM method, three types of fluctuations are applied to investigate the impacts on infection scale. In detail, fundamental fluctuations with $\sigma_i = 0.0004$ ($i = 1, 2$) and $\sigma_i = 0.004$ ($i = 3, 4, 5, 6, 7, 8$) are employed in Figs. 5–9. The moderate fluctuations with $\sigma_i = 0.001$ ($i = 1, 2$) and $\sigma_i = 0.01$ ($i = 3, 4, 5, 6, 7, 8$) are employed in Fig. 9. Meanwhile, amplified fluctuations with $\sigma_i = 0.01$ ($i = 1, 2$) and $\sigma_i = 0.1$ ($i = 3, 4, 5, 6, 7, 8$) are employed in Fig. 4 and Table 2.

3.2. Comparison of infection scale

The sensitivity analysis of $\mathcal{R}_0$ and $\mathcal{R}_0^s$ are carried out using data from January 2022 to December 2022, the contour plots for the protection efficiencies towards acutely infected population and the conversion rate are displayed in Fig. 4, in which protection efficiency towards acutely infected population exhibits the highest sensitivity for $\mathcal{R}_0$ and $\mathcal{R}_0^s$. The protection efficiency is regarded as control measure. Case (1,0,0), Case (0,1,0) and Case (0,0,1) belong to single-measure; Case (1,1,0), Case (1,0,1) and Case (0,1,1) belong to double-measure; Case (1,1,1) belongs to triple-measure; Case (0,0,0) belongs to none-measure. The changes of protection efficiency in Figs. 5 and 6 and conversion rate in Fig. 6 demonstrate the significant differences of HCV infection scale. Especially, HCV infection scale with protection efficiency in Fig. 5 points out that Case (1,1,1) is the smallest infection scale, and Case (0,0,0) is the largest infection scale. Meanwhile, for exposed population, acutely infected population, chronically infected population, and treated population, Figs. 7 and 8 reflect that the enhancement of protection efficiency towards acutely infected population and conversion rate lead to the decline of HCV infection scale.

3.3. Estimation of reproduction number

The estimations of reproduction numbers are conducted using main parameter values in Table 1, formula (3) of toy model (1) and formula (4) of modified model (2). Further, basic reproduction number $\mathcal{R}_0$ and stochastic reproduction number $\mathcal{R}_0^s$ are compared by phases in Table 2 with measures (single-measure, double-measure and triple-measure), which indicate that the declining tendencies of reproduction numbers. Meanwhile, the research shows that the saved scale of HCV at most is approximately 24.63×10^6 as of the end of 2022 in Fujian Province.

3.4. Tendency prediction

The 2023–2035 HCV tendency predictions for acutely infected population and chronically infected population (on left panel) and treated population (on right panel) are plotted in Fig. 9. The 2023–2035 HCV tendency predictions with moderate fluctuations are widely distributed in terms of infection scale than those with fundamental fluctuations. The monthly infection scale of Fujian Province grows slowly in terms of approximately 19–109 infections. Through reducing public health hazards and alleviating the healthcare burden in years, the overall HCV growth tendency of Fujian Province is consistent with the nation-wide elimination objective.

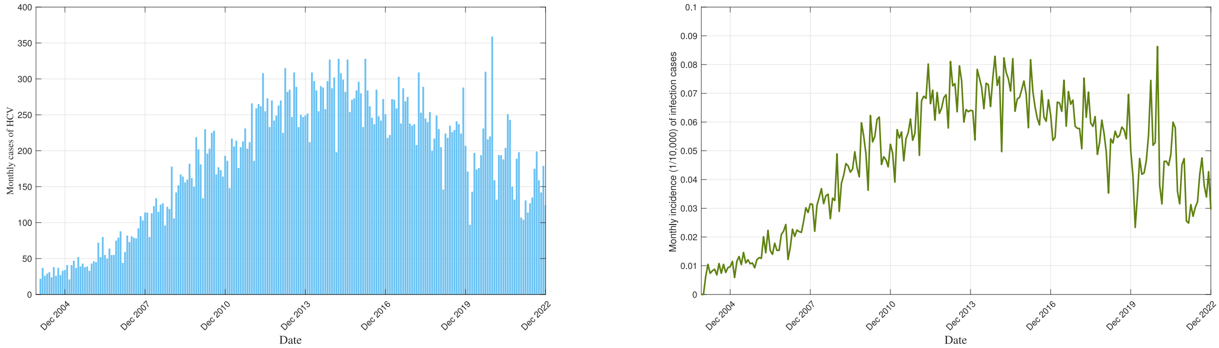

Fig. 2. Monthly surveillance data and monthly incidence of HCV from Fujian Provincial Center for Disease Control and Prevention from 2004 to 2022.

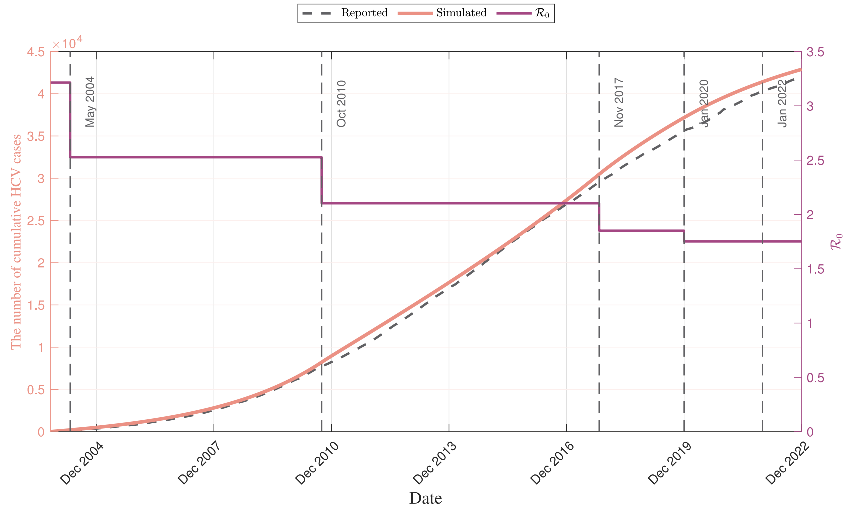

Fig. 3. Optimal fitting with two-month awareness delay by least squares method (Orange solid curve) against 2004–2022 monthly surveillance data of Fujian Province (Black dashed curve). Basic reproduction number by phases (Purple solid line).

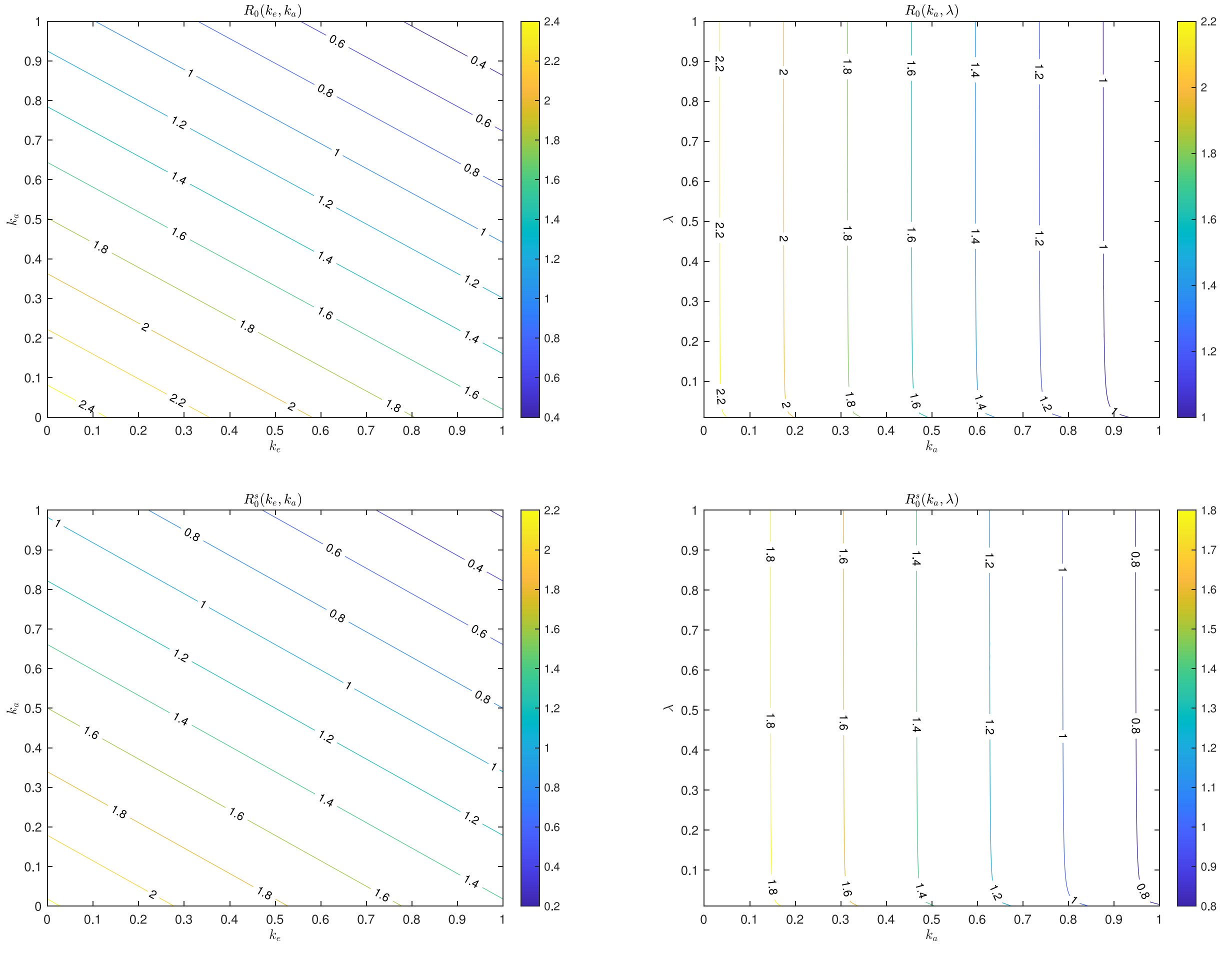

Fig. 4. Contour plots of sensitivities for $\mathcal{R}_0$ and $\mathcal{R}_0^s$ from January 2022 to December 2022.

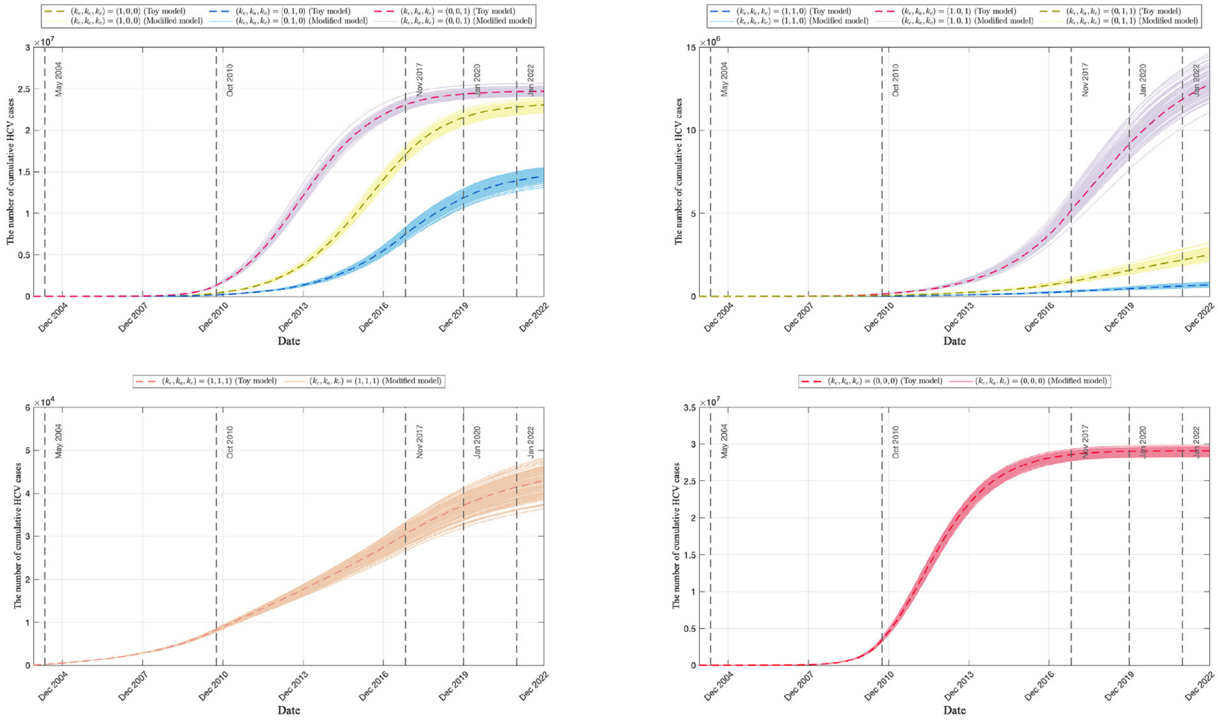

Fig. 5. Impacts of protection efficiencies on HCV infection scale with single-measure (Top Left), double-measure (Top Right), triple-measure (Bottom Left), none-measure (Bottom Right). Dashed curves are created by toy model (1), solid curves are created by modified model (2) with 100 sample paths.

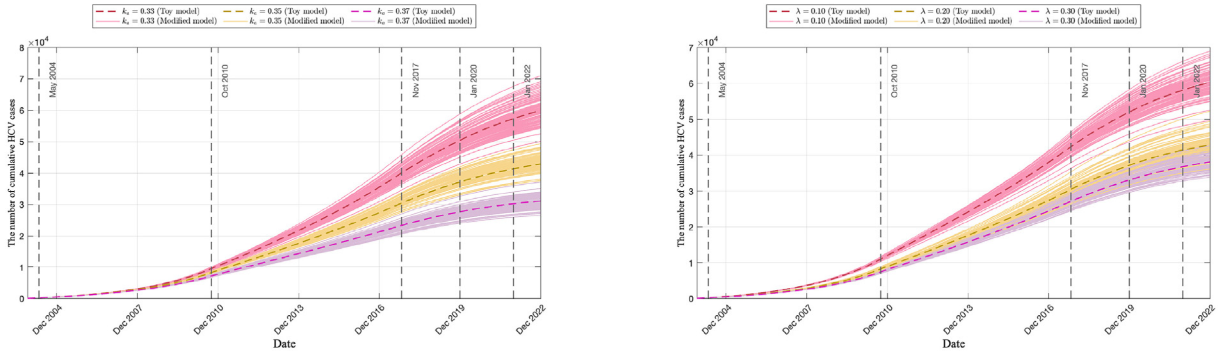

Fig. 6. Impacts of protection efficiency k_a and conversion rate λ on HCV infection scale. Dashed curves are created by toy model (1), solid curves are created by modified model (2) with 100 sample paths.

4. Discussion and conclusion

We proposed the SEACTR models (i.e., the susceptible, the exposed, the acutely infected, the chronically infected, the treated, the recovered) with protection awareness, in which the susceptible population was separated into the susceptible population without protection awareness and the susceptible population with protection awareness; the protection awareness was described by protection efficiency and conversion rate for exposed population, acutely infected population, chronically infected population. The 2004–2022 monthly surveillance data of HCV from the Fujian Provincial Center for Disease Control and Prevention were collected and the implementations of nation-wide control measures of HCV were considered. The reproduction number and infection scale for HCV were concerned in this study.

The expression of basic reproduction number (i.e., $\mathcal{R}_0$) of toy model (1) was derived by using of next generation matrix method. Moreover, the expression of stochastic reproduction number (i.e., $\mathcal{R}_0^s$) of modified model (2) was obtained by dynamic analysis method in (Wang et al., 2025). The awareness delay of HCV was taken as two months and main parameter values were taken from Table 1, using the 2004–2022 monthly surveillance data (Fig. 2), the optimal fitting of toy model (1)

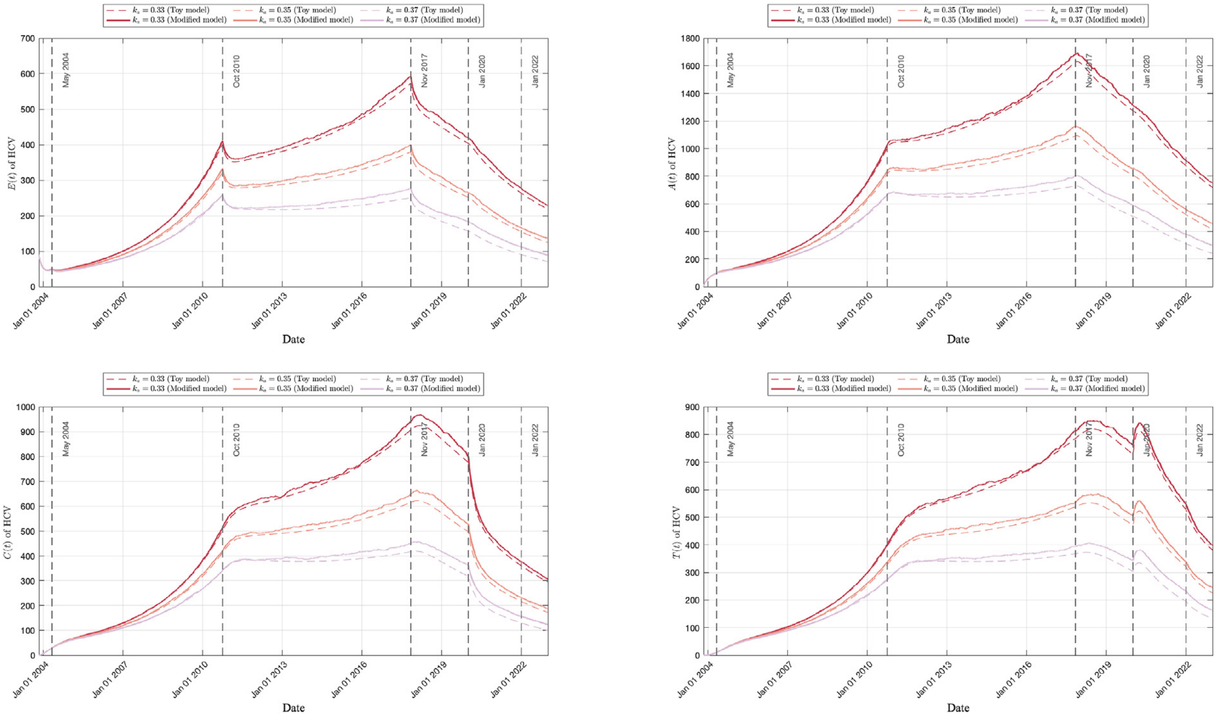

Fig. 7. Current scales of exposed population, acutely infected population, chronically infected population and treated population for HCV. Dashed curves are created by toy model (1), solid curves are created by modified model (2). Orange curves are performed for $k_a = 0.35$ by main parameters in Table 1, red curves are for $k_a = 0.33$, purple curves are for $k_a = 0.37$.

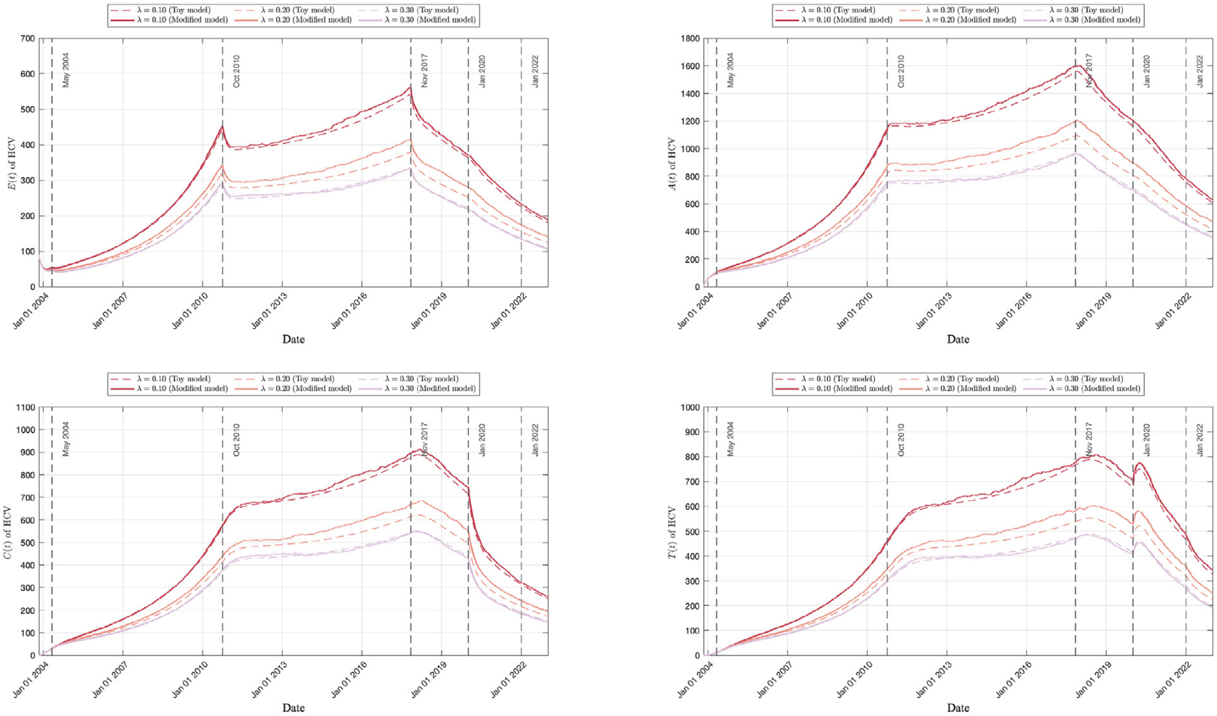

Fig. 8. Current scales of exposed population, acutely infected population, chronically infected population and treated population for HCV. Dashed curves are created by toy model (1), solid curves are created by modified model (2). Orange curves are performed for $\lambda = 0.20$ by main parameters in Table 1, red curves are for $\lambda = 0.10$, purple curves are for $\lambda = 0.30$.

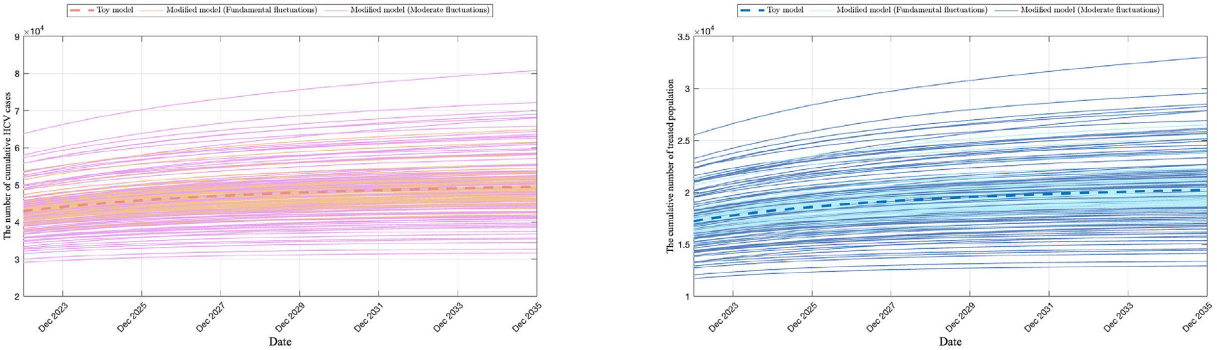

Fig. 9. The tendency predictions of HCV of Fujian Province in 2023–2035. Cumulative numbers for acutely infected population and chronically infected population (Left) and for treated population (Right). Dashed curves are created by toy model (1), solid curves are created by modified model (2) with 200 sample paths.

Table 2
Estimations of reproduction numbers of HCV by phases.

Item	Period (Start-End) [a]	Single-measure						Double-measure						Triple-measure	
		Case (1,0,0)		Case (0,1,0)		Case (0,0,1)		Case (1,1,0)		Case (1,0,1)		Case (0,1,1)		Case (1,1,1)	
		$\mathcal{R}_0$	$\mathcal{R}_0^s$	$\mathcal{R}_0$	$\mathcal{R}_0^s$	$\mathcal{R}_0$	$\mathcal{R}_0^s$	$\mathcal{R}_0$	$\mathcal{R}_0^s$	$\mathcal{R}_0$	$\mathcal{R}_0^s$	$\mathcal{R}_0$	$\mathcal{R}_0^s$	$\mathcal{R}_0$	$\mathcal{R}_0^s$
Phase 1	2003–11 - 2004–04	4.62	4.04	4.05	3.55	4.44	3.90	3.72	3.25	4.11	3.60	3.55	3.12	3.21	2.82
Phase 2	2004–05 - 2010–09	3.54	3.10	3.20	2.81	3.51	3.09	2.88	2.52	3.19	2.80	2.85	2.51	2.53	2.22
Phase 3	2010–10 - 2017–10	2.93	2.56	2.67	2.35	2.93	2.58	2.39	2.09	2.64	2.32	2.39	2.11	2.10	1.85
Phase 4	2017–11 - 2019–12	2.55	2.24	2.32	2.04	2.62	2.31	2.05	1.80	2.35	2.07	2.12	1.87	1.85	1.63
Phase 5	2020–01 - 2022–12	2.38	2.10	2.15	1.90	2.52	2.22	1.88	1.66	2.25	1.98	2.02	1.79	1.75	1.55
Average [b]	2003–11 - 2022–12	3.05	2.67	2.76	2.43	3.06	2.70	2.47	2.17	2.77	2.43	2.48	2.19	2.19	1.93
Infection scale [c]	2003–11 - 2022–12	23.02	–	14.42	–	24.67	–	0.68	–	12.77	–	2.49	–	0.04	–
Saved scale [d]	2003–11 - 2022–12	22.98	–	14.38	–	24.63	–	0.64	–	12.73	–	2.45	–	–	–

[a] 2003–11 is for YYYY-MM with Y (year) and M (month).
[b] Average $= (P_1 \times V_1 + P_2 \times V_2 + P_3 \times V_3 + P_4 \times V_4 + P_5 \times V_5)/(P_1 + P_2 + P_3 + P_4 + P_5)$, where P_i and V_i are the periods and values that $\mathcal{R}_0$ and $\mathcal{R}_0^s$ belong to.
[c] Units of infection scale and saved scale are $\times 10^6$.
[d] Saved scale is calculated by taking the difference between the infection scale with Case (1, 0, 0) [or, Case (0, 1, 0), Case (0, 0, 1), Case (1, 1, 0), Case (1, 0, 1) and Case (0, 1, 1)] and the infection scale with Case (1, 1, 1).

was performed by least squares method, in which the declining tendency of basic reproduction number by phases was provided (Fig. 3). The sensitivities of basic reproduction number and stochastic reproduction number with respect to protection efficiency and conversion rate were analyzed (Fig. 4), and the impacts of protection efficiency to acutely infected population was significant. Further, the HCV infection scale and reproduction number with measures (single-measure, double-measure, triple-measure, and none-measure) were compared using toy model (1) and modified model (2) (Fig. 5 and Table 2). If single-measure was implemented only for chronically infected population, then the results showed that average basic reproduction number and average stochastic reproduction number were respectively 3.06 and 2.70, further that the infection scale as of the end of 2022 was approximately 24.67 $\times$ 10^6 and the saved scale was approximately 24.63 $\times$ 10^6. If double-measure was taken into account for both exposed population and acutely infected population, then the results showed that average basic reproduction number and average stochastic reproduction number respectively dropped to 2.47 and 2.17, which weakened the HCV transmission in Fujian Province, further that the infection scale and the saved scale as of the end of 2022 were significantly reduced to approximately 0.68 $\times$ 10^6 and 0.64 $\times$ 10^6. Moreover, if protection efficiency towards acutely infected population and conversation rate were taken larger values, then the HCV infection scale apparently declined (Figs. 6–8). In addition, the investigations on the fluctuations showed that fundamental fluctuations, moderate fluctuations and amplified fluctuations created more uncertainty to modified model (2) when transmission dynamics of HCV in Fujian Province was considered. Then, the 2023–2035 tendency predictions with fundamental fluctuations and moderate fluctuations were displayed. In comparison with infection scale with fundamental fluctuations, the infection scale with moderate fluctuations was widely distributed (Fig. 9).

The main results of this study revealed that HCV transmission of Fujian Province turned to be slow because basic reproduction number and stochastic reproduction number showed the declining tendencies by phases, which matched nation-wide prevention and control tendency of HCV on the Chinese mainland. One important and effective measure was the enhancement of protection awareness of the population with HCV. In this study, the education and publicity aiming at the enhancement of protection awareness were encouraged to be applied on social media and platforms, of which the enhancement of protection awareness for acutely infected population significantly reduced the HCV infection scale. The 2023–2035 tendency prediction of HCV transmission in Fujian Province slowed down to approximately 19–109 monthly infections through reducing public health hazards and alleviating the healthcare burden, to achieve the nation-wide elimination objective of Chinese government.

CRediT authorship contribution statement

Liangwei Wang: Writing – original draft, Visualization, Formal analysis, Data curation, Conceptualization. **Fengying Wei:** Writing – review & editing, Supervision, Project administration, Methodology. **Zhen Jin:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Xuerong Mao:** Writing – review & editing, Supervision, Project administration, Methodology. **Shaojian Cai:** Writing – review & editing, Data curation. **Guangmin Chen:** Writing – review & editing. **Kuicheng Zheng:** Writing – review & editing. **Jianfeng Xie:** Writing – review & editing, Supervision, Project administration.

Ethics approval and consent to participate

The ethical approval and individual consents were exempted as the aggregated data were used in this study.

Data and material availability

The data that supported this article may be available upon reasonable request to the corresponding author.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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